AD NUMBER

AD884770

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; Apr 1971. Other requests shall be referred to Commander, Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH 45433.

AUTHORITY

AFFDL ltr, 25 Sep 1972

AD884270

DDC FILE COPY

CONTROL - DISPLAY INTEGRATION PROGRAM

AFFDL-TR-70-174

ANALYSIS OF HUMAN FACTORS DATA FOR ELECTRONIC FLIGHT DISPLAY SYSTEMS

CLARENCE A. SEMPLE, JR.

RAYMOND I. HEAPY

ERNEST J. CONWAY, JR.

MANNED SYSTEMS SCIENCES, INC.

KEITH T. BURNETTE, 1LT./USAF

AIR FORCE FLIGHT DYNAMICS LABORATORY

TECHNICAL REPORT AFFDL-TR-70-174

APRIL 1971

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FGR), Wright-Patterson Air Force Base, Ohio 45433.

AIR FORCE FLIGHT DYNAMICS LABORATORY

AIR FORCE SYSTEMS COMMAND

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

DISCLAIMER NOTICE

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

400-May 1971-CO305-19-71-642

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) MANNED SYSTEMS SCIENCES, INC. 8949 Reseda Blvd., Suite 206 Northridge, California 91324	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

ANALYSIS OF HUMAN FACTORS DATA FOR ELECTRONIC FLIGHT DISPLAY SYSTEMS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report November 1969 -- December 1970

5. AUTHOR(S) (First name, middle initial, last name)

Clarence A. Semple, Jr.
Ernest J. Conway, Jr.
Raymond J. Heapy
Keith T. Burnette, 1Lt./USAF

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January, 1971	570	397

8a. CONTRACT OR GRANT NO. F33615-70-C-1132 b. PROJECT NO. 6190-07-005 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFFDL-TR-70-174 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FGR), Wright-Patterson Air Force Base, Ohio, 45433.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Flight Dynamics Laboratory Wright-Patterson Air Force Base Ohio 45433

13. ABSTRACT

This report presents the results of a review of 1178 technical documents dealing with human factors considerations in electronic flight display systems. Design-oriented human factors data are presented for the following families of design considerations: display size, information coding, alphanumerics, scale legibility, visual acuity, display system resolution, flicker, contrast ratio requirements, and environmental variables including ambient illumination, vibration and acceleration. Quantitative, design-oriented functional relationships are emphasized. Research recommendations are made where existing data were found inadequate for design use. A model is presented for organizing the variables impacting upon human performance as a function of electronic flight display system design.

DD FORM 1473

UNCLASSIFIED

Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Acceleration						
Alphanumerics						
Ambient Illumination						
Bandwidth						
Cathode Ray Tubes						
Chromatic Aberration						
Chromaticity						
Cockpit Displays						
Color Coding						
Computer Generated Display						
Contrast Ratio						
Critical Flicker Frequency						
Display Size						
Electronic Displays						
Eye Adaptation						
Flash Coding						
Flicker						
Font						
Human Engineering						
Human Performance						
Illumination						
Image Quality						
Information Coding						
Legibility						
Matrix Symbols						
Persistence						
Phosphor						
Raster Displays						
Refresh Rate						
Research Requirements						
Resolution						
Scale Reading						
Scale Shape						
Shape Coding						
Solid State Displays						
Spherical Aberration						
Stroke Width To Height						
Symbol Blur						
Symbol Luminance						
Symbol Size						
Symbol Spacing						
Target Detection						
Vibration						
Viewing Angle						
Visual Accommodation						
Visual Acuity						
Width To Height						

UNCLASSIFIED
Security Classification

ANALYSIS OF HUMAN FACTORS DATA FOR ELECTRONIC FLIGHT DISPLAY SYSTEMS

CLARENCE A. SEMPLE, JR.
RAYMOND J. HEAPY
ERNEST J. CONWAY, JR.

MANNED SYSTEMS SCIENCES, INC.

KEITH T. BURNETTE, 1LT./USAF

AIR FORCE FLIGHT DYNAMICS LABORATORY

FOREWORD

This technical report documents the results of a literature review and analysis conducted under USAF Contract Number F33615-70-C-1132 by MANNED SYSTEMS SCIENCES, INC., 8949 Reseda Blvd., Suite 206, Northridge, California 91324.

The objective of the investigation was to perform a comprehensive review and analysis of the human factors literature relating to electronic flight display system design, and to develop research recommendations where necessary.

The contract was initiated under Project 6190, "Control Display for Air Force Aircraft and Aerospace Vehicles", which is managed by Mr. John Kearns, III, Project Engineer and Principal Scientist. It was administered by the Control Systems Research Branch (FGR), Flight Control Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. The work was initiated by Mr. James Townsend, Group Leader, as a part of Task No. 6190-07, "Human Factors Engineering for Aircraft Control Display Systems" and was performed under the guidance of Captain Eugene Rathswohl and Lt. Keith Burnette as Task Engineers. The work effort covered the period from November, 1969 through December, 1970.

This report was submitted by the authors in January, 1971.

This technical report has been reviewed and is approved.

William D Knox
WILLIAM D. KNOX, Lt Col, USAF
Chief, Control Systems Research Branch
Flight Control Division
Air Force Flight Dynamics Laboratory

ABSTRACT

This report presents the results of a review of 1178 technical documents dealing with human factors considerations in electronic flight display systems. Design-oriented human factors data are presented for the following families of design considerations: display size, information coding, alphanumerics, scale legibility, visual acuity, display system resolution, flicker, contrast ratio requirements, and environmental variables including ambient illumination, vibration and acceleration. Quantitative, design-oriented functional relationships are emphasized. Research recommendations are made where existing data were found inadequate for design use. A model is presented for organizing the variables impacting upon human performance as a function of electronic flight display system design.

TABLE OF CONTENTS

	Page
List of Figures	xi
List of Tables	xxv
SECTION I INTRODUCTION	1
SECTION II RELATIONSHIP OF DESIGN CONSIDERATIONS: A MODEL	10
Introduction	10
Model	10
Display Size Considerations	12
Information Coding Considerations	14
Alphanumeric Considerations	16
Scale Legibility Considerations	18
Factors Affecting Visual Acuity	20
Display System Resolution Considerations	22
Flicker Considerations	24
Legibility Contrast Considerations	26
Environmental Variable Considerations	28
SECTION III DISPLAY SIZE FOR FLIGHT CONTROL	
Introduction	30
Target Detection Tasks	31
Noise	31
Pip Size	33
Radar Imagery	33
Continuous Control Tasks	34
Introduction	34
Design Variable Relationships	36
Research Evidence	38
Conclusions	49
SECTION IV INFORMATION CODING	51
Introduction	51
Shape Coding	52
Introduction	52
Form Perception	56
Symbol Alphabets	64
Summary	81
Radar-Type Symbology	81
Conclusions	101
Recommendations	101

TABLE OF CONTENTS (Continued)

	Page
Color Coding	103
Introduction	103
Hue Alphabet Size	106
Summary	116
Advantages of Color Coding	118
Summary	134
Disadvantages of Color Coding	135
Conclusions and Recommendations	140
Flash Rate Coding	142
Introduction	142
Summary	146
SECTION V ALPHANUMERIC DESIGN CONSIDERATIONS	147
Introduction	147
Font or Style	151
Introduction	151
Non-Electronic Display Studies	151
Conclusions	155
Electronic Display Studies of Font	160
Conclusions	162
Symbol Size and Proportion	165
Symbol Height	165
Conclusions	167
Symbol Width-to-Height	168
Conclusions	170
Symbol Stroke Width-to-Height	170
Conclusions	174
Symbol Spacing	176
Conclusions	176
Words	177
Conclusions	177
Edge (Off-Center of Tube) Displayed Symbology	177
Conclusions	179
Viewing Angle	179
Symbol Blur	179
Conclusions	180
Matrix Symbol Generation Techniques	180
Introduction	180
Cathode Ray Tube Matrix	181
Conclusions	190

TABLE OF CONTENTS (Continued)

	Page
Solid State Matrix Symbols	190
Conclusions.	196
Research Requirements	196
SECTION VI SCALE LEGIBILITY CONSIDERATIONS	202
Introduction	202
Considerations of Display Integration	203
Considerations of Research Methodology	204
Mission-Imposed Scale Reading Accuracy Requirements	209
Scale Shape	212
Nonlinear Scales	218
Numbering Scale Interval Values	219
Scale-to-Readline Distance	220
Stroke Width of Scale Markings	222
Subdividing Major Scale Intervals: Reading to Nearest Scale Mark	225
Number of Scale Divisions	225
Spacing of Minor Graduation Marks	225
Circular Scales: Interpolation	228
Linear Scales: Interpolation	232
Introduction	232
Interpolation Accuracy	232
Comparison Among Studies	239
Checkreading Cues	240
Research Recommendations	240
SECTION VII FACTORS AFFECTING VISUAL ACUITY	245
Introduction	245
Luminance Level	248
Background Luminance	248
Surround Luminance	252
Effects of Contrast	259
Direction of Contrast	261
Eye Adaptation Level	266
Exposure Time and Visual Acuity	276

TABLE OF CONTENTS (Continued)

	Page
Spherical Aberration	278
Chromatic Aberration	282
Accommodation of the Eye	285
Dynamic Visual Acuity	285
Retinal Image Location	293
Point Source of Light	297
Summary and Integration of Facts	300
Research Recommendations	307
SECTION VIII DISPLAY SYSTEM RESOLUTION CONSIDERATIONS	311
Introduction	311
CRT Resolution	314
Solid-State Resolution	316
CRT Display Resolution	317
Image Formation and Transmission	317
Spot Size	325
Channel Bandwidth	330
Vertical and Horizontal Resolution	334
Line Written Display Resolution	339
Summary	339
Solid-State Display Resolution	341
Visual Acuity and Resolution	344
CRT-Type Display Research Requirements	345
Solid-State Resolution Research Requirements	348
CRT Display Symbol Resolution Requirements	350
Introduction	350
Lines per Symbol Height--Alphanumerics	352
Conclusions	364
Geometric and Pictorial Symbols	364
Conclusions	374
Quality of Equipment	376
Conclusions	376
Video Bandwidth	380
Conclusions	384
Image Quality	385
Edge-Gradients	385
Display Jitter	389

TABLE OF CONTENTS (Continued)

	Page
Image Smear	389
Grain Size	391
Summary	393
SECTION IX FLICKER FACTORS	394
Introduction	394
Observer Characteristics	397
Individual Reactions	397
Persistence of Vision	398
Display Chromaticity	399
Illumination Intensity	402
Display Parameters	405
Introduction	405
Display Luminous Intensity	406
Conclusions	411
Display Refresh Rate	411
Light-to-Dark Ratio	419
Phosphor Characteristics	426
Conclusions	432
Information Up-Date Rate	432
Summary and Conclusions	437
Research Recommendations	441
SECTION X LEGIBILITY CONTRAST REQUIREMENTS	444
Introduction	444
Ambient Illumination	447
Canopy and Windscreen Transmitivity	447
Eye Adaptation Levels and Sun Visors	448
Illumination Incident Upon Display Faces	457
Panel-Mounted Displays	457
Projected Displays	459
Display Background Luminance	460
Filter Types	461
Conclusions	467
Contrast Polarity	470
Emitter Color	472
Early Contrast Ratio Recommendations	475
Computations of Contrast Ratios	475

TABLE OF CONTENTS (Continued)

	Page
Research on Contrast Ratios	480
Panel-Mounted Displays	481
Projected Displays	496
Research Recommendations	498
SECTION XI ENVIRONMENTAL VARIABLES	506
Introduction	506
Ambient Illumination	506
Vibration	510
Introduction	510
Visual Acuity	511
Summary	516
Dial Reading	518
Acceleration	524
Introduction	524
Visual Grayout or Blackout	525
Visual Fields	525
Reaction Time	525
Dial Reading	525
Brightness Discrimination Threshold	526
Visual Acuity	529
Conclusions	530
Research Recommendations	531
References	533

LIST OF FIGURES

Figure Number		Page
1	System Variables Influencing Display Usability	7
2	Design Variable Clusters Influencing Electronic Flight Display Design	11
3	Model of Display Size Considerations	13
4	Model of Information Coding Considerations	15
5	Model of Alphanumeric Considerations	17
6	Model of Scale Legibility Considerations	19
7	Model of Factors Affecting Visual Acuity	21
8	Model of Display Systems Resolution Considerations	23
9	Model of Factors Influencing Flicker	25
10	Model of Considerations Affecting Legibility Contrast Requirements	27
11	Model of Environmental Variable Considerations	29
12	Probability of Target Detection on a PPI Display as a Function of Display Size and Noise	32
13	Probability of Target Identification from Radar Imagery as a Function of Display Size and Scale Factor	35
14	Distribution of Touchdown Points	40
15	Variability of Touchdown Points as a Function of Practice	40
16	Accuracy of Roll Angle Maintenance as a Function of Display Size and Roll Angle	43
17	Average Absolute Error of Roll Angle Judgements as a Function of Roll Angle Magnitude	45
18	Effects of Display Size and Display Viewing Angle on the Amount of Displacement of the Horizon Line Resulting from a 15^{o} Increment in Pitch	46

LIST OF FIGURES (Continued)

Figure Number		Page
19	AAE as a Function of Display Size	48
20	RMS Error as a Function of Display Size and Pitch Attitude Controlled	48
21	Information Coding Section	53
22	Forms and Variations Used by Casperson	65
23	Forms Used by Sleight	66
24	Description of Figures Used in First Study by Bitterman et al.	69
25	Required Luminance Threshold as a Function of Parameter/Area	69
26	Forms Used in Experiment V	70
27	Brightness and Form Threshold as a Function of Length of Critical Detail	71
28	The 20 Symbols Selected by Bowen et al.	72
29	The Interaction Effect of Noise, Distortion, and Blur Upon the Probability of Correct Response	75
30	Symbols Used by Williams and Falzon	77
31	Figures Used by Williams and Falzon	79
32	Representative Figures Used in Study by Attneave	84
33	General Appearance of the Matrix Forms at the Four Different Blur-Disc Diameters Measured in Inches	85
34	The Twenty Targets Used in the Experiment	86
35	Probability of Error (a) and Search Time (b) as a Function of the Amount of Blur Present	87
36	The 24 Targets Used in the Study Ranging in Size from 3 Cells (Number 6) to 78 Cells (Number 1)	88

LIST OF FIGURES (Continued)

Figure Number		Page
37	Search Time and Frequency of Error as a Function of Visual Angle Subtended by Target	89
38	Search Time and Probability of Error as a Function of Matrix Cell Size	90
39	Schematic View of Target Symbols and Target Circles Used by Gerathewohl et al. . .	90
40	Symbols Used by Dardano and Donley	91
41	Scanning Time as a Function of Symbol Size	95
42	Arrangement of Symbols on 3 x 5 Cards for Experiment 4	98
43	Smallest Difference in Wavelength that can be Detected as Different in Hue Using the Comparative Method of Discrimination	108
44	The Ten Absolutely Identifiable Spectral Hues Suggested by Baker and Grether	108
45	Percentage Error in Color Identification as a Function of the Number of Practice Runs (Averaged for All S's) for Selected Target (T) and Background (B) Purity Combinations	113
46	Response Time as a Function of Percent Misregistration	120
47	Subject Performance for Symbol Colors Averaged Over All Conditions	120
48	Number of Omissions as a Function of Color	121
49	Mean Exposure Time Required by Each Group as a Function of the Number of Days	124
50	Search Time as a Function of the Number of Symbols with Target's Color	125
51	Mean Total Information Gained Per Message	128
52	The Five Code Categories Compared by Hitt	129

LIST OF FIGURES (Continued)

Figure Number		Page
53	Search Time as a Function of Display Density and Target Identity	132
54	Colors and Symbols Used by Smith et al.	133
55	Average Counting Time for Color Coding and Three Shape Codes as a Function of Display Density	134
56	The Standard Landolt-C Ring	137
57	Mean Correct Responses for All S's for Each Stimulus Level and Each Condition	139
58	Tracking Error as a Function of Visual Angle for Experiment II	144
59	Tracking Errors as a Function of Training for Experiment II Coding Methods	145
60	Mackworth Alphanumerics	152
61	AND 10400 Numerals	152
62	Standard Leroy Alphanumerics	152
63	Berger Numerals	154
64	AMEL Numerals	154
65	Garamond Bold Letters	154
66	NAMEL Letters	154
67	Lincoln/Mitre Alphanumerics	156
68	Lansdell Numerals	156
69	Foley Numerals	156
70	MIL-M-18012 Alphanumerics	158
71	MIL Standard MS-33558 Alphanumerics	158
72	Courtney Alphanumerics	161
73	Long Gothic Alphanumerics	163

LIST OF FIGURES (Continued)

Figure Number		Page
74	Murray Alphanumerics	163
75	Lincoln/Mitre Dot Matrix Alphanumerics	187
76	Sixteen Segment Alphanumerics	191
77	Seventeen Segment Alphanumerics	191
78	Twenty-three Segment Alphanumerics	192
79	Twenty-seven Segment Alphanumerics	192
80	Thirty-eight Segment Alphanumerics	193
81	Reading Errors and Interpretation Times for Selected Altimeter Designs	213
82	Probability of Minor Scale Reading Errors (1 or 2 Units) as a Function of Scale Interval Length	229
83	Scale Reading Error as a Function of Scale Interval Length	231
84	Reading Errors and Times for Vertical Scales as a Function of Scale Interval Length	233
85	Relative Error of Visual Interpolations in Percent of Scale Interval as a Function of the Size of the Scale Interval	235
86	Absolute Error of Visual Interpolations in MM. as a Function of the Size of the Scale Marked Interval	235
87	Mean Absolute Error as a Function of Vertical Scale Interval Length and Number of Graduation Marks Per Interval . . .	236
88	Mean Absolute Error as a Function of Horizontal Scale Interval Length and the Number of Graduation Marks Per Interval	236
89	Factors Affecting Visual Acuity	246

LIST OF FIGURES (Continued)

Figure Number		Page
90	Visual Acuity as a Function of Background Luminance	249
91	Acuity as a Function of Background Luminance	249
92	Visual Acuity as a Function of Background Luminance and Luminance Contrast	251
93	Minimum Visual Angle as a Function of Background Luminance	251
94	Threshold Visual Angle as Determined by Brightness of Greater Surround	253
95	Acuity as a Function of Luminance of Immediate Surround	254
96	Acuity as a Function of Surround Luminance with Small Area Luminance Held Constant	254
97	Effects of Various Surround to Background Luminance Ratios	258
98	Minimum Detectable Target Size for 50% Probability of Detection as a Function of Background Luminance and Target Contrast	260
99	Visual Acuity as a Function of Contrast	261
100	Acuity as a Function of Direction of Contrast	262
101	Contrast Threshold as a Function of Area of Stimulus	263
102	Effects of the Interaction Between Color and Brightness Contrast with Direction of Contrast on Reading Time	264
103	Visual Acuity as a Function of Target and Background Luminance	265
104	Instantaneous Threshold as a Function of Pre-Adapting Luminance Level	267

LIST OF FIGURES (Continued)

Figure Number		Page
105	Rate of Loss of Dark Adaptation after Exposure to Light	268
106	Adaptation as a Function of Pre-Adaptation Time	269
107	Threshold Luminance as a Function of Pre-Adapting Luminance	269
108	Acuity as a Function of Test Field and Visual Adaptation Level	271
109	Instantaneous Threshold as a Function of Time in the Dark	272
110	Time for Detection as a Function of Degree of Contrast	273
111	Dark Adaptation Curves for Centrally Fixated Areas of Different Sizes	275
112	Luminance Threshold as a Function of Wavelength of the Test Stimulus	275
113	Threshold Luminance as a Function of the Region of the Retina Stimulated	275
114	Acuity as a Function of Duration of Exposure of Viewed Object	277
115	Contrast Thresholds as a Function of Target Size and Duration of Exposure	277
116	Relative Luminous Efficiency of Light Entering the Pupil in Horizontal Plane Through the Center of the Eye	279
117	Effects of Glare-Source Luminance Upon Perceived Size and Shape of Circles, Squares, and Triangles	280
118	Effects of Glare-Source Intensity on Apparent Size	281
119	Relative Sensitivity of the Human Eye to Different Hue Wavelengths	283
120	Amplitude of Accommodation as a Function of Age	286

LIST OF FIGURES (Continued)

Figure Number		Page
121	Threshold Values for All Subjects Grouped According to Pre-Test Performance Levels	288
122	Difference Between Two Subjects in Degradation of Dynamic Acuity with Increasing Angular Velocity	288
123	Visual Acuity as a Function of Horizontal Versus Vertical Movement	289
124	Acuity as a Function of a) Illumination Level and b) Angular Velocity	290
125	Isochronal Threshold Velocity as a Function of Luminance Level and Duration of Exposure	292
126	Isochronal Threshold Velocity as a Function of Duration of Exposure with Target Luminance as a Parameter	293
127	Visual Acuity at Different Viewing Angles Away from the Visual Axis as a Function of Background Luminance	294
128	Relative Visual Acuity at Different Angles from the Fovea for Photopic Vision	296
129	Minimum Size of Retinal Image of a Point Source as Derived from Several Investigations	299
130	Critical Visual Angle for Point Source of Light Versus Critical Angles for Area Targets	299
131	Minimum Visual Angle a Light Source can Subtend and Still be Observed (Plotted as a Function of Luminance of the Light Source	300
132	Interaction Between Visual Acuity, Background Luminance, Luminance Contrast, and Duration of Exposure	301
133	The Five Basic Curves Related to Visual Acuity	302

LIST OF FIGURES (Continued)

Figure Number		Page
134	(This Figure Deleted)	--
135	Object Point to Image Spread	317
136	Normal Spread Function	318
137	Formation of the Image Point	320
138	Representation of Relationships Between Measures of Resolution	323
139	Display Spot Size as a Function of Grid (G_1) Voltage	326
140	Display Spot Size as a Function of Beam Current for Various Sample Tubes, B_1, B_2 and B_3 (Note E_B = 7,000 Volts, E_{G_2} = +320 Volts, E_{G_2} = +550 Volts, and E_{G_2} = +700 Volts)	326
141	Halation Effect Produced by Reflection of Beams by Interior Surfaces of Faceplate . . .	328
142	The Diffusion Effect Resulting from a Non-Flat Screen	328
143	Resolution (n = Number of Scale Lines) as a Function of Bandwidth (f_m) and Frame Rate (N)	333
144	Resolution as a Function of Bandwidth (f_m) and Frame Rate (N)	333
145	Resolution as a Function of Bandwidth (f_m) and Frame Rate (N)	333
146	Typical Raster Scanned Display and Component Signals	335
147	Typical Scanning Lines Showing Alternating Dark and Light Picture "Elements" Transmitted in (a) and out (b) of Synchronism	336
148	Typical Television Frame Interlacing	338
149	Solid State Type Display Resolution Variables	342

LIST OF FIGURES (Continued)

Figure Number		Page
150	Schematic of Light Transmission Process in "Total Resolution System" from Display Surface to the Eye of the Observer	346
151	Average Identification Time as a Function of Vertical Resolution for the Small Amount of Practice Group, Part I	355
152	Identification Errors as a Function of Vertical Resolution for the Small Amount of Practice Group, Part I	355
153	Average Identification Time as a Function of Resolution for the Additional Practice Group, Part II	356
154	Identification Errors as a Function of Resolution for the Additional Practice Group, Part II	356
155	Mean Percent Correct Symbol Identification, Averaged Overall 36 Symbols, for Group 2 (Viewed Slides in Increasing Order of Difficulty) at Each of the 9 Levels of Symbol Resolution	358
156	Mean Correct Response Time for the Average Televised Symbol at Each Level of Resolution and for the Solid-Symbol Condition	358
157	Probability of Detection and Recognition as a Function of Number of Active Scan Lines	368
158	Probability of Correctly Identifying Map Symbols as a Function of the Number of TV Lines per Symbol Height	369
159a	Target Recognition Time as a Function of Horizontal Resolution	371
159b	Probability of Correct Recognition as a Function of Horizontal Resolution	371
160	Geometric Figures Used by Hemingway and Erickson	372

LIST OF FIGURES (Continued)

Figure Number		Page
161	Percentage Correct Response as a Function of (a) Angular Subtense and (b) Scan Lines per Symbol Height	372
162	Comparison of Smoothed Data from Baker and Nicholson, Hemingway and Erickson	374
163	The Number of Scan Lines and the Angular Subtense Requirements for 80% (a), 90% (b) and 95% (c) Levels of Correct Responses	375
164	Average Symbol Identification Times	379
165	Average Error Percentage	379
166	Results of Study by Shanahan Using 100% (a), 81% (b), and 27% (c) Contrast Between Target and Background	383
167	Distribution of Density in Image of Knife-Edge	387
168	Influence of Edge-Gradient Diffusion on Search Efficiency	388
169	Perception of a Bipartite Field	388
170	Effectiveness of Visual Performance as a Function of Grain Size and Scale	392
171	(This Figure Deleted)	--
172	Mean Visual Persistence Decay Curve for the High Intensity 50 and 25 Millisecond Conditions	400
173	Mean Visual Persistence Decay Curve for the Low Intensity 50 and 25 Millisecond Conditions	400
174	Spectral Sensitivity of the Eye Compared to Commonly Used CRT Phosphor Wavelengths	401
175	CFF for Varying Retinal Illumination Levels	403

LIST OF FIGURES (Continued)

Figure Number		Page
176	CFF as a Function of Illumination Level for Three Retinal Positions	403
177	Emitted Display Luminance as a Function of Refresh Rate and Phosphor Type	407
178	Luminance Output as a Function of Phosphor Concentration	409
179	CFF as a Function of Critical Screen Brightness in Ft. Lamberts (with Other Factors Held Constant) for White Light	410
180	Refresh Rate as a Function of Luminance for Flicker-Free Performance of Several Commonly Used Phosphors	416
181	Relationship Between Perceived Brightness, and Flash Rate for Several Light-to-Dark Ratios	420
182	CFF as a Function of Different Light-Dark Ratios	422
183	Visibility of Flashing Light Source	422
184	The Inhibitory Effect of a Second Stimulus on Reaction Time to a Primary Stimulus	423
185	CFF as a Function of Exposure Duration and LDR for High (1,000 Ft.L.) and Low (100 Ft.L.) Luminance Levels	425
186	Terminology of Luminescence During Rise and Decay Processes	427
187	Representative Phosphor Decay Times	429
188	Critical Fusion Frequency as a Function of Emitted Luminance and Phosphor Type	431
189	Performance as a Function of Information Presentation Rate	436
190	Performance as a Function of Flash Duration (% Time On)	436

LIST OF FIGURES (Continued)

Figure Number		Page
191	Approximate Flicker Stages and the Resulting Observer Reactions	438
192	Relationship Among Factors Affecting Symbol-Display Contrast Ratio Requirements	446
193	Percent Increase Required in Contrast Ratios as a Function of the Ratio of Surround Luminance to Display Background Luminance	450
194	Comparison of Percent Contrast Between Pairs of Adjacent Shades of Gray for Open Monitor Versus Average of Three Wire Mesh Filters Under High Ambient Lighting (2,000 Ft. Lamberts)	466
195	Relative Amounts of Radiant Flux Required to Stimulate Rods and Cones	474
196	Photopic and Scotopic Relative Luminosity Curves	474
197	Contrast Thresholds of the Eye	477
198	Visual Acuity as a Function of Contrast	477
199	Correction Factors for Eye Adaptation Mismatch	478
200	Display Reading Latency as a Function of Symbol Luminance and Display Clutter . . .	483
201	Emitted Symbol Luminance Required for 99% Display Legibility	489
202	Percent Contrast Required for 99% Display Legibility	491
203	Emitted Symbol Luminance Required for EL Displays to be Judged Comfortably Bright 50% of the Time	495
204	Range of Natural Illumination on Earth from the Sun and Moon	509

LIST OF FIGURES (Continued)

Figure Number		Page
205	Mean Decrements of Visual Acuity (Solid Curve) and Mean Standard Deviation (Dotted Curve), (a) During Vibration, (b) After Vibration	513
206	Percentage Increase in Error (per 1/1,000 Inch Amplitude) as a Function of Frequency of Vibration	518
207	Approximations of Dials Used by Taub	520
208	Errors as a Function of Frequency, Acceleration Level and Dial Type for Vibration in the X-Axis	520
209	Errors as a Function of Frequency for Vibration in the X-Axis	521
210	Power Density Spectrum of Vibration Input Acceleration	522
211	Summary of Mean Error Scores as a Function of the Experimental Conditions . . .	523
212	Reading Errors as a Function of Acceleration and Luminance Levels	527
213	Relationship of Brightness Discrimination Threshold to Level of Positive Acceleration for Four Background Luminance Levels	528
214	Visual Acuity as a Function of Acceleration	530

LIST OF TABLES

Table Number		Page
1	Minimum Set of Mutually Exclusive Display Design Variables Impacting Upon Design Tradeoffs	5
2	Display Dimensions Studies by Cross and Bittner	42
3	Summary of Results of Study by Collier	59
4	Summary of Results of Study by Helson and Fehrer	61
5	Summary of Results Comparing "Compactness" and Apparent Brightness	62
6	Ranking of Forms for Studies Reviewed	63
7	(a) Mean Sorting Time and (b) Relative Discriminability of the Six Forms	67
8	Percentage of Correct Recognition	73
9	Optimum Set of Symbols	74
10	Assignment of Figures to Experimental Categories	78
11	Search Time Rank Order of Symbols	80
12	Relative Discriminability of the Four Targets	92
13	Frequency of Reports (a), of Misidentification (b), and Responses (c), for the Experimental Targets	93
14	Total Occasion Each Target was Preferred for a Given Meaning Recorded for Each Symbol . . .	97
15	Summary of Performance Showing Total Errors (E) and the time in Minutes (T) for Each Symbol (S)	99
16	Summary of Data Obtained with Absolute Judgements of Spectral Colors	109

LIST OF TABLES (Continued)

Table Number		Page
17	Recommended Color Alphabets: Chart A for 8 Hue Alphabet, Chart B for 7 Hue Alphabet, Chart C for 6 Hue Alphabet and Chart D for 5 Hues	111
18	Colors and Purity Levels Used by Bishop and Crook	112
19	Color Recommendations by Meister and Sullivan	115
20	Summary of Recommendations	117
21	Relative Discriminability of the Colors Examined	119
22	Visual Dimension Variations Used in the Experiment	122
23	Mean Score for the 4 Single and the 10 Compound Dimensions	123
24	Average Information Gained (in Bits) for Color Alphabet and for Numeric Alphabet	127
25	Rank Order of Code Categories as a Function of the Type of Task	130
26	Colors Used by Smith	131
27	Sizes of C-Ring Apertures in Inches and Minutes of Arc and Seconds of Visual Angle	138
28	Summary of Results	138
29	Non-Electronic Display Font Comparisons: A Summary	157
30	MIL-M-18012 Numeral and Letter Dimensions	159
31	Accuracy and Rate of Symbol Identification for the Howell and Kraft Study	166
32	Total Number of Errors and Percentage Error for Various Width-Height Proportions with Transillumination and .20 Second Exposure Time	169

LIST OF TABLES (Continued)

Table Number		Page
33	Total Number of Errors and Percentage Error for Various Width-Height Proportions with Transillumination and .04 Second Exposure Time	169
34	Average Number Correct Responses per Subject for Various Numeral Width-to-Height Percentages	170
35	Mean Scores on Oral Reading Task with Capital Letters	171
36	Mean Scores on Oral Reading Task with Capital Letters	173
37	Mean Percentage Correct Scores for Reading Transilluminated Block Style Capital Letters When Exposure Time is .04 Second. Each Subject Read Five Cards of Three Letters for Each Stroke Width and Brightness Combination	175
38	Mean Percentage Correct Scores for Reading Transilluminated Block Style Capital Letters When Exposure Time is .20 Second. Each Subject Read Five Cards of Three Letters for Each Stroke Width and Brightness Combination	175
39	Symbol Size and Rates for Center and Edge Displays	178
40	Experimental Conditions for Vartebedian Study . .	182
41	Average Viewing Time and Error Rates for the Six Conditions	184
42	Average Ranking 1-Best to 6-Worst for the Six Conditions	184
43	Accuracy and Rate of Symbol Identification	184
44	Experimental Conditions for the Anderson Study . .	185
45	Confusion Matrix for the Anderson Study	186

Table Number		Page
46	The Trend to Significant Differences Between Standard and Segmented Numeral Designs as a Function of Operator Task Complexity . .	189
47	Summary of Font Characteristics	195
48	Percent Correct Response	195
49	Research Recommendations: A Summary	199
50	Maximum Ranges, Rates of Change and Accuracies Associated with the Control of Selected Flight Data Parameters	211
51	Frequency of Errors and Interpretation Times for 97 Pilots Reading Altitude from Nine Experimental Displays	214
52	Time and Error Scores for Open Window, Circular and Vertical Scales	216
53	Some Effects of Scale Interval Length and Pointer-to-Scale Clearance on the Frequency of Interpolation Errors and Reading Time for Subject-Paced Viewing	223
54	Time and Error Scores for Four Conditions of Quantitative Scale Reading	227
55	Probability of Scale Reading Error as a Function of the Interval Between Minor Graduation Marks	227
56	Mean Display Reading Times in Seconds as a Function of Scale Orientation, Interval Length and the Number of Graduation Marks per Interval	237
57	Experimental Background and Surround Brightnesses and Corresponding Surround-to-Background Brightness Ratios . . .	257
58	Visual Acuity Degradation as a Function of Body Orientation	297
59	Relationship of Factors Affecting Visual Acuity	304

LIST OF TABLES (Continued)

Table Number		Page
60	Direction of Effect Produced by Changes in Factors Affecting Visual Acuity	305
61	Some Relationships Among Various Measures of Resolution	315
62	Conversion Table for Several Measures of Display System Resolution where σ Equals the S.D.	321
63	Spot Sizes as a Function of Tube Sizes	327
64	Summary of Eye-Equipment System Parameter Interactions	347
65	Recommendations for Variables to be Researched in the Context of Solid-State Display Resolution	349
66	Approximate Scan Line and Symbol Sizes as a Function of the Total Number of Active Scan Lines in the Display	350
67	Experimental Conditions for Shurtleff and Owen Study	353
68	Statistically Significant Differences Between Successive Resolution Pair Comparisons for Small and Additional Practice Parts Using Average Identification Times and Accuracy of Identification as Performance Measures	354
69	Experimental Conditions for the Elias, Sandowsky and Rizy Study	359
70	Experimental Conditions for the Elias Study . . .	360
71	Experimental Conditions for the Bell Study	361
72	Mean Response Time (in seconds) for 190 Symbols Shown at Four Television Resolutions to Three Subjects	362
73	Number of Errors for the 190 Symbols Shown at Four Television Resolutions to Three Subjects	363

LIST OF TABLES (Continued)

Table Number		Page
74	Experimental Conditions for the Shurtleff, Marsetta and Showman Study	365
75	Visual Angles of Subtense Required for 85 and 99 Percent Accuracy of Identification	366
76	Identification Rates for 85 and 99 Percent Accuracy of Identification	366
77	Specifications for the 525 and 945 Line Raster Television Systems	377
78	Experimental Conditions for the Shurtleff and Owen Study	378
79	Summary of Results in Experiment by Shurtleff . .	381
80	The Effects of Video Signal Bandwidth and Target Contrast on Target Identification Ability	382
81	Summary of Recommended Number of Lines per Symbol Height	385
82	Jitter Effects on Line Perception	390
83	Summary of Determinants of Flicker	396
84	Summary of Findings on Persistence of Vision . . .	399
85	(a) CFF and Persistence Rates for a Number of Commonly Used Phosphors, and (b) Manufacturer's Specifications for Representative Computer Controlled Displays	413
86	Summary of Representative Refresh Rate Recommendations	418
87	Summary of Findings by Anderson et al.	424
88	Rank Ordering of Phosphors According to their Flicker Producing Qualities	430
89	Relative Phosphor Brightness Corrected to Human Eye	430

LIST OF TABLES (Continued)

Table Number		Page
90	Characteristics of Electronic Industries Association Registered Standard Phosphors	433
91	Representative Observer-Display Interactions . . .	440
92	Representative Tradeoff Functions	441
92	Light Transmission and Haze Values	447
93	The Influence of 11% Transmitivity Visors Upon Legibility Contrast Ratio Requirements for an EL Numeric Readout	454
94	Mean Distance in Feet at which Direction of Break in Landolt C-Ring could be Identified	456
95	T-39 Instrument Panel Luminance Measurements . . .	458
96	Measured Luminance Values (Ft. Lamberts) for Several Shades of Gray with 6.5 and 2,000 Ft. Lamberts of Ambient Light	465
97	Measures of Reflected Display Luminance Under Conditions of High Illuminance Incident Upon Display Faces	469
98	Some Typical Color Names Associated with Luminance Wavelengths Comprising the Visible Spectrum	473
99	Minimum Comfortable-to-Use Luminance and Percent Contrast Data	484
100	Median Legibility Contrast Ratios Required for High Contrast Electroluminescent Alphanumerics Legibility	486
101	Electroluminescent Display Legibility Luminance Data for Bargraph and Numeric Readout Displays	488
102	Mean Legibility Percent Contrasts for Bargraph and Numerics as a Function of Whether a Helmet-Mounted Visor was Worn . . .	492

LIST OF TABLES (Continued)

Table Number		Page
103	Fiftieth Percentile Percent Contrasts and Emitted Luminances Required to Produce Comfortably Bright EL Displays	494
104	HUD Display Symbol Dimension	496
105	Photometric Data on Combining Glasses	497
106	Ninety Percent Threshold Data for Fine (Angle of Attack) and Coarse (Horizon Angle) Tasks	499
107	Summary of Comfort Level Symbol Contrasts Ratio for Most and Least Sensitive Subjects	500
108	Summary of Selected Measurements of Natural Illumination in Earth's Atmosphere	507
109	Summary of Percentage Degradation of Visual Acuity During (a) and One Minute After Cessation (b) of Vibration	514
110	Results from Loeb Showing % of Acuity Decrement per Estimated Head Movement	515
111	Amplitude and Frequencies of Vibration in Study by Dennis	516
112	Performance Degradation as a Function of Vibration Amplitude and Frequency	517
113	Thresholds for Positive Acceleration	525

SCOPE OF STUDY

The intent of the study herein documented was to collect, synthesize, analyze, and to present, in a quantitative form, the currently available design data needed by an aircraft display designer to produce advanced electronic flight displays which satisfactorily meet the pilots perceptual requirements. The ultimate goal toward which the program is directed is the evolution of a complete set of display specifications which would assure satisfactory individual displays given only individual task and mission requirements have been initially specified.

In the past, a great deal of effort in the general area of determining human perceptual characteristics to enhance display design capability has been carried out; however, only recently have attempts been made to organize, analyze and consolidate this information. The present study represents the first attempt to do this for data specifically dealing with human perceptual characteristics as they relate to the design of electronic flight displays.

It is anticipated that the study results presented here, when used by knowledgeable display designers should produce significant advances in the perceptual quality of future individual electronic flight control displays. It must, however, be emphasized that much experimental research remains to be done before the goal of a self-contained design handbook adequate for the formulation of an arbitrary display capable of satisfying any chosen flight control task, and using any of the many electronic display media and techniques available, is fully realized.

The human factors perceptual data available to date in the literature has dealt with CRT presentations. The problems encountered with the design of other flexible format displays, such as: light emitting diode, planar gas discharge, thin film electroluminescent phosphor, liquid crystal, or other possible X-Y matrix addressable displays, are presently covered only through engineering interpolation of the existing CRT data. In addition, the perceptual requirements imposed by the use of the CRT display itself remains only partially documented in the literature. To compensate for this lack of information the present study has, in such cases, used the best available non-CRT data to fill the voids identified in the literature. This procedure is strictly valid only where supporting experimental results using CRT's justify it. In large part such testing has not been carried out, and caution must therefore be used in applying the results.

Because a knowledge of what constitutes the minimum information required to specify a pilot acceptable display is at best only incompletely known, the data needed for the design of such displays is often available only in terms of variables not applicable to display design, or in variable ranges unimportant to such designs. The present effort attempted wherever possible to put this data in a format useful for display design. It non-the-less remains true that variables of specific design interest have either been neglected or have been controlled insufficiently during the human factors experiments. Such data has been included where no better data is available together with a caution as to the applicability of the data. Due to the lack of uniformity of experimental technique between different studies and due to the subsequent influence this has on the results, both the human factors data and as much as possible of the experimental environment and procedure used to obtain it, are provided in the report.

To sum up, much experimental research remains to be done before a handbook containing data completely independent of the method used to acquire it will become a reality. In the interim the present study will provide the design engineer with a valuable design tool not previously available to him. It should be reiterated, however, that the value of this design tool depends on whether a willingness exists on the part of the designer to objectively evaluate the applicability of the human perceptual data rather than to use it blindly without regard to the experimental environment in which it was taken and under which it is valid.

SECTION I

INTRODUCTION

There is only one reason for a display to exist. It provides an operator with information which he needs in order to control, manage or monitor a system process. If all processes could be managed, monitored or controlled through direct observation of the processes, there would be no requirement for either symbolic or pictorial information displays.

Aerospace requirements for flight control, system monitoring, management, navigation, reconnaissance, weapon delivery and other functions, however, typically cannot be satisfied through direct observation of the controlled process. Reasons for this center around the facts that the processes either cannot be directly observed, can be only partially observed, or information necessary to control the process within predetermined limits cannot be determined from either total or partial direct process observations. Finally, it is frequently the case in current and projected aerospace systems that the amount of information which must be input by the crewmembers in order to control flight, navigation, protection or weaponery processes simply exceeds the human capability for information input and processing. As a result, many functions are allocated to on-board computing equipment. Consequently, synthetic information displays are commonplace in aerospace systems. The displays provide the man-process interface which is necessary to combine hardware capabilities with human flexibilities and capabilities in order to accomplish total system-mission objectives.

Technology provides two fundamental means of presenting information to aerospace crewmembers. One means is electro-mechanical information display; the second means, which holds considerable promise for the future, is the electronic information display. An electronic flight display is a device which can produce an electronically generated image that is directly viewable by the pilot. An example of one group of electronic flight displays is the cathode ray tube (CRT). CRT's have been used extensively for the display of radar information and for the generation of gun sight display content. CRT's also are receiving attention as flight data displays, and rear-ported CRT's have been used in the design of projected map displays. Also included in the general class of electronic flight displays are such diverse solid state display media as electro-luminescence, light emitting diodes, planar gas discharge devices, and liquid crystal displays. While the majority of such media are still highly developmental, alphanumerics, bar-graphs and X-Y matrices have been built as display devices, and current development efforts are being directed toward further improvement of solid state display media.

Electronic displays, including head-up projections of display information (HUD) have gained wide use-acceptance, and it is quite predictable that they will be even more prevalent in future system designs. This is not simply a fortuitous occurrence. Electronic displays frequently are the only suitable means for the presentation of certain types of information. Radar imagery is one example. Additional examples include television imagery, infrared imagery, and certain laser-sensor information.

Limited instrument panel space and differing mission-segment requirements also provide cases which argue in favor of electronic information displays. Requirements for time-sharing are central to this argument. Additional arguments arise from the simultaneous and concurrent display of information from multiple sensors. Requirements for display of computed target track or path history also argue in favor of electronic displays over electromechanical information presentations. High in importance are the versatility factors associated with electronic display systems. Such factors include: shades of gray presentation, variable scale factors, display format flexibility, and the partial deletion of display content of lesser importance in order to present information of immediate importance such as cautionary of failure warning signals.

Electronic displays also provide numerous engineering advantages over their electromechanical counterparts in the areas of reliability, weight, and digital and analog operation, as well as responses to physical inputs such as G-forces and vibration. Finally, promising benefits of the solid state display media must be brought to the front because of their even better potential for engineering advantages over current electronic information display techniques.

Past, current and projected trends in display system technology, therefore, insure a future for both directly viewed and projected electronic display systems. This future is predicated not only upon requirements for multi-function, time-shared, reliable displays, but also upon the usability of the electronic displays which engineering technologies are and will be capable of producing. It is at the usability juncture where engineering technology and human factors technology must unite. Sensor and display capabilities and limitations must be matched with corresponding capabilities and limitations of the human operator. This is necessary in order to provide a man-machine system interface which is responsive not only to engineering skill levels in sensor and display design, but also to mission requirements, environmental variables and operator capabilities and tasks. Only in this fashion can total man-machine aerospace system success be insured.

In the preceding paragraph, the concept "insuring the success of a display system" was used. What is meant by insurance? Insurance is a wager that the future will turn out well, and this wager is made by the individual who feels that he has a sufficient understanding of the future in order to make the wager worthwhile. Second, what is meant by a system? A system is an integrated combination of equipment variables, human capabilities and procedures, enhanced or encumbered by environmental factors, and directed towards the accomplishment of pre-specified mission objectives. "Insuring the success of a display system", therefore, requires a detailed and quantitative understanding of the significant engineering and human factors data which impact upon the design of a man-machine display system for the purpose of satisfying mission requirements.

During the past decade, engineering advances in the design of sensing, computing and display devices have been outstanding. One must ask, however, are the outstanding engineering advances meaningful, and have the expenditures of engineering research and development resources been efficiently and systematically directed toward known needs for improvement? Answers to these and similar questions will never be simple and straightforward. Any answer, however, cannot be developed outside of a total man-machine system context. In other words, answers to such questions cannot be based upon hardware performance alone. There is only one reason for a display to exist. It provides an operator with information which he needs in order to control, manage or monitor a system process. Furthermore, the operator must accomplish these functions within prescribed mission requirements and constraints. Sensing, computing and display hardware comprise only one portion of the total display system. The characteristics, limitations, and procedures of the human operator comprise additional and very significant portions of the man-machine display system. Therefore, to determine the goodness of a display system, one must be able to specify total man-machine system performance requirements. This, in turn, means that one must be able to define human perceptual and performance requirements, and translate these requirements into quantitative specifications of the type necessary in the system design and evaluation process.

In a probabilistic world, there are precious few unequivocally true statements of fact. However, one such statement has been: To date, there has existed no systematic, comprehensive and quantitative review and analysis of human factors requirements and data for airborne electronic flight display system design. Stated differently, the human factors state-of-the-art for airborne electronic flight display system design and requirements for subsequent human factors research have been unknown. This is of considerable importance because human factors requirements provide critical design goals toward which engineering research and design should be directed.

Nevertheless, airborne electronic information display systems have been and are being designed and developed. More frequently than not, human factors have been considered in the designs. The degrees to which all relevant factors have been considered are, however, frequently in question. Furthermore, the degrees to which human factors research resources have been wasted rediscovering already known answers to previously asked questions also are in question. Finally, the frustration of display system design engineers is known to be frequent and great when they repeatedly find that hopefully useful human factors research has produced only subjective "alternative X is better than alternative Y" design guidelines, when what is actually needed are quantitative functional relationships between display design variables and operator or system performance variables.

Limited reviews and analyses of the human factors literature have been completed in order to provide guidance to electronic display system designers. The review documents which exist (Refs. 206, 232 and 294) are generally limited in scope. Only two of the reports (Refs. 232 and 294) have attempted to systematically and comprehensively identify quantitative human factors design data, and neither of these has directly addressed electronic flight displays. A primary objective of the current study was to fill such voids.

One must ask, what are the human factors information requirements of the electronic display system design engineer? Stated differently, what is the minimum set of mutually exclusive, independent design variables with which the electronic display system design engineer may describe his system, and what design-oriented human factors data are needed to allow the engineer the maximum flexibility in making trade-offs within the context of the independent variable set?

The listing of display design variables shown in Table 1 was developed in an attempt to establish the minimum set of mutually exclusive, independent variables which can be used to define, from an engineering standpoint, all characteristics of virtually any electronic display, either CRT or solid state. An examination of the content of Table I reveals that no variable in the table can be defined in terms of other variables shown. Thus, each variable may be considered as an independent variable. It may also be seen from the table that two or more independent variables frequently must be considered in order to relate display physical characteristics to operator performance requirements. An example is symbol-display contrast, wherein independent variables influencing display background luminance must be considered in conjunction with emitter luminance and light transmission coefficients. It is apparent, therefore, that although the display design variables are independent, they may be highly related to one another in terms of identifying and

Table 1. Minimum Set of Mutually Exclusive Display Design Variables Impacting Upon Design Trade-offs.

- Ambient light intensity in which displays must operate
- Reflection coefficients of display material
- Transmission coefficients of display face materials
- Required range of light emission intensities of emitting elements
- Number of distinguishable light intensity levels required
- Required uniformity of light emissions
  - a) at high intensities
  - b) at low intensities
- Allowable tolerances for light intensity, transmitivity and reflectivity factors
- Color of background
- Color of emitters
- Shape of symbols to be displayed
- Dimensions of symbols to be displayed
- Symbol placement and dynamic interrelationships
- Information update rate requirements
- Emitter (or spot) size and shape
- Diffusitivity of boundary regions of individual emitters
- Allowable (or required) frequency of AC or pulsed drive signal
- Emitter placement or density
- Size of background
- Average light intensity of emitters
- Display refresh rate requirements
- Size of total display face

specifying operator-imposed design requirements. Because of this, it also is apparent that meaninful human factors design data will not necessarily exist for each of the independent variables shown in Table 1.

Human factors in display system design covers a considerable range of design factors, ranging from the specification of characteristics for simple display elements, such as symbols, through specification of total display format, taking into account not only display elements, but also the integration of displayed information in relation to operator encoding characteristics and task requirements. Also involved are vehicle, sensor and computer characteristics.

The technical activities reported herein did not attempt to cover the total spectrum of human factors in display system design. Scope of the effort is shown graphically in Figure 1, where it can be seen that physical display characteristics and operator detection and recognition task performance were emphasized. Influences of environmental factors including illuminance, vibration and G-forces also were considered.

An overall objective of the effort involved the accumulation and integration of quantitative human performance data for display elements in general. This was done in order to provide data which might be generalized to the broadest range of electronic display applications and which could be useful independent of particular display formats. Thus, the content of this report deals with making symbology discriminable, visible, legible and flicker-free throughout the spectrum of operational environments encountered by Air Force aircraft. Furthermore, quantitative functional relationships between selected design variables and indices of human performance have been emphasized over vague, qualitative human factors recommendations in an attempt to provide human performance data which may be quantitatively related, when possible, to independent hardware design variables and combinations of such variables. Finally, where valid, quantitative design data could not be found, research recommendations have been specified. Specific technical objectives for the study are listed below:

- Perform a comprehensive survey of all human factors literature and on-going research relating to the man-electronic flight display system interface.

- Perform a comprehensive and systematic analysis and integration of all valid, quantitative design-related human factors data in order to determine and identify the interactive relationships between electronic flight display characteristics and pilot performance.

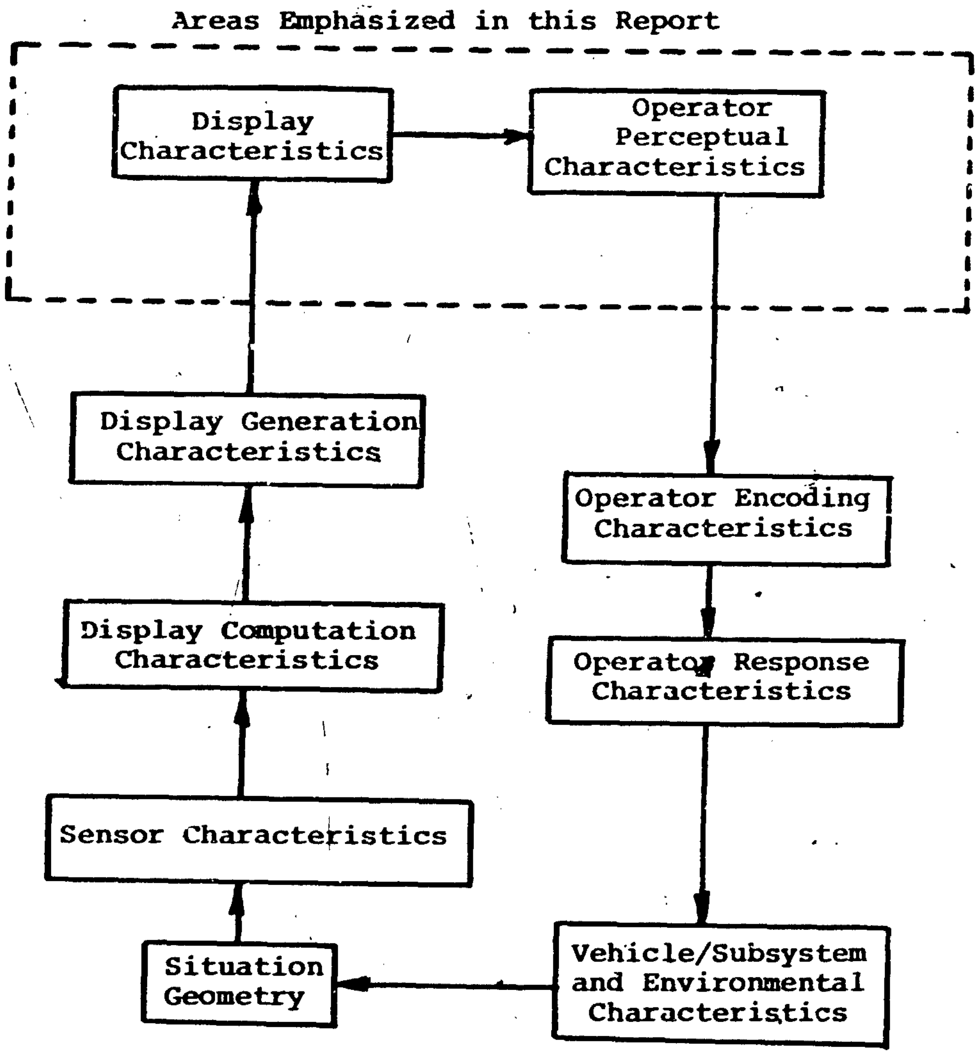


Figure 1. System Variables Influencing Display Usability.

- Develop a heuristic model or procedures for integrating and relating available human factors data for electronic flight display system design.

- Prepare a comprehensive, design-oriented technical discussion of available information and findings.

- Develop research recommendations for investigating problems, data voids and data inconsistencies identified during the program.

In accomplishing the objectives set forth for the program, a comprehensive literature search was accomplished. All known sources of technical information were reviewed, and a total of 1178 reports, articles, journal publications and books were identified as potentially relevant. In addition, a Defense Documentation Center Work Unit Survey was reviewed and requests for data and information were published in several trade publications in order to identify on-going or yet unpublished data of possible relevance. The remainder of this report presents the best available data for electronic flight display design, along with research recommendations where existing data are not adequate. As might be expected, not all available data were sufficiently quantitative or generalizable to be of value. Not all data were judged to be experimentally sound enough for valid usage, although where extreme data shortages were identified, the best available data are given, with the shortcomings identified. Design-oriented data presented throughout the remainder of this report are based upon the best information which is currently available. Organization of the data is discussed more fully in the next section.

SECTION II

RELATIONSHIPS OF DESIGN CONSIDERATIONS: A MODEL

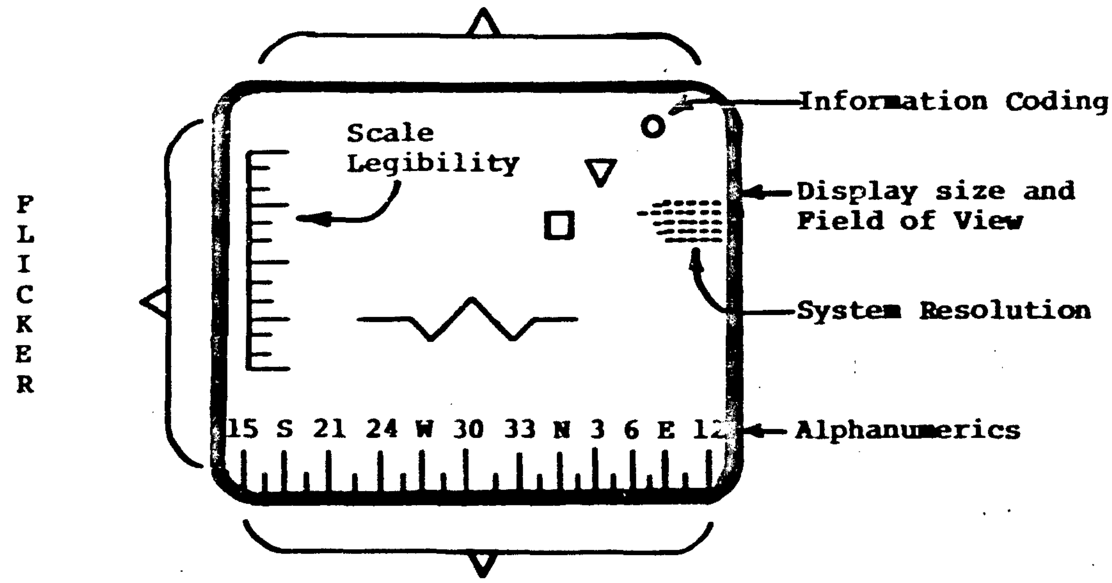
INTRODUCTION

The number of variables which the human factors engineer must consider when participating in electronic flight display design or when planning related research is quite sizeable. Additionally, many variables interact, and if the interactions are ignored, design inputs or research activities will suffer accordingly. In an effort to provide some organization for the design variables and data discussed in the remainder of the report, it was felt necessary to formulate conceptual models which could serve as means for clustering design variables and other considerations into logical groupings, as well as showing salient relationships among the constituents of each group. The remainder of this section presents our attempts to provide some order to what could be a very cumbersome technical area.

MODEL

Figure 2 presents a definition of the major clusters of variables which are of direct concern in the proper human factors design of electronic flight displays. Each of the major clusters is addressed separately in subsequent figures in an attempt to show the interrelationships of design variable considerations within each of the major categories shown in Figure 2. Subsequent major sections of the report also are organized in keeping with the major categories shown in Figure 2. Consequently, the additional figures within this section provide the reader with a general outline of the technical content contained within the remainder of this report.

Environmental Factors of
Ambient Illumination,
Vibration and Acceleration



Symbology Brightness
and
Contrast Requirements

Figure 2. Design Variable Clusters Influencing Electronic Flight Display Design.

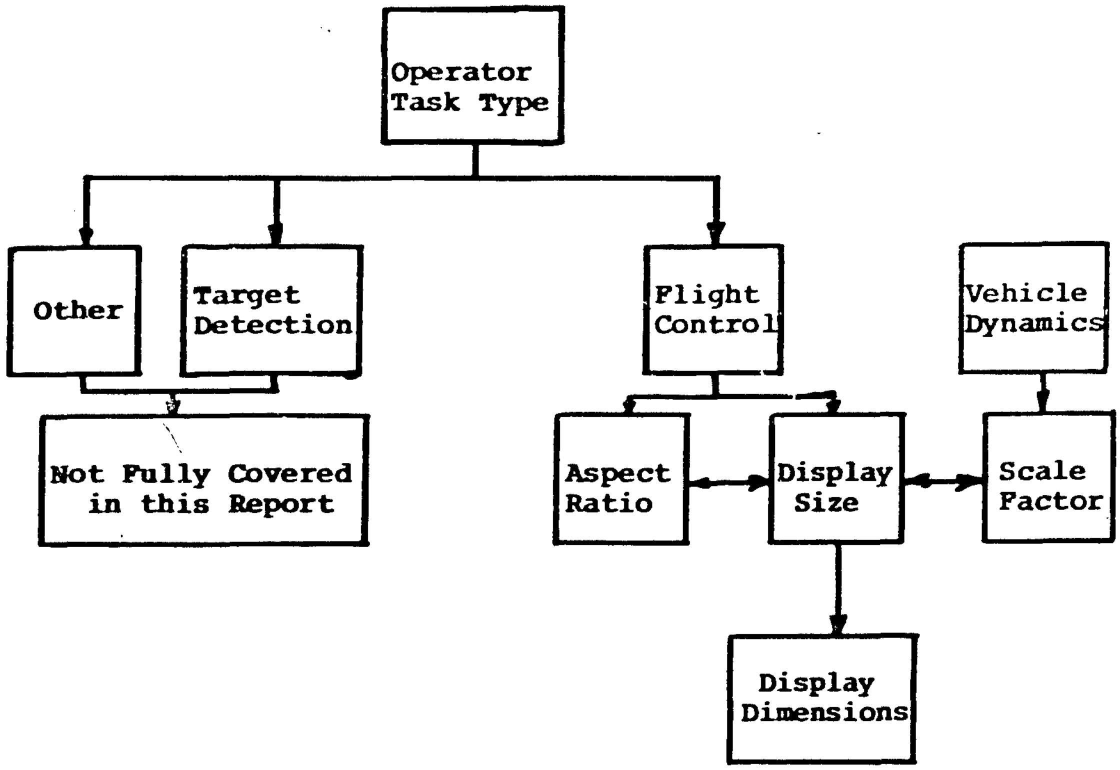


Figure 3. Model of Display Size Considerations.

Information Coding Considerations

The efficiency with which a symbol transmits information to the observer depends upon: (1) the nature, type and amount of information presented, (2) number of discrete symbols required, (3) nature of observer tasks, (4) the environment under which the display is viewed. Symbols should be selected on the basis of their ability to be located and identified with 100% observer performance under "worse case" viewing conditions. Relationships among key factors are shown in Figure 4.

Early symbology studies attempted to ascertain the "optimum" or "best" symbol. Depending upon the idiological orientation of the experimenter (Gestalt or non-Gestalt), the "best" symbol form turned out to be "circles" or "triangles" (respectively). Later studies attempted to establish equally discriminable symbol alphabets, while another series of studies examined symbols presented on radar-type displays. Results generally indicate that simple outlined geometric forms elicit optimum observer performance on CRT-type displays. Studies specifically addressing electronically generated airborne displays viewed under operational conditions could not be identified.

The selection of color codes for visual displays requires the following considerations: (1) the visual environment under which it is to be viewed, (2) nature of information, (3) nature of symbol to be color coded, (4) the hue selected. The advantages and disadvantages of color codes include: (1) excellent for locating and counting tasks, for displaying additional information, and for enhancing performance of other codes, while (2) they are less effective for identification tasks, lose discriminability under high luminous conditions, in the presence of color-symbol misregistration and when used in conjunction with small symbols. The necessity of color codes should be carefully evaluated.

Flash rate coding provides an excellent dimension for displaying critical information requiring immediate attention. It is limited, however, by limited discriminability, fatigue, and annoyance factors.

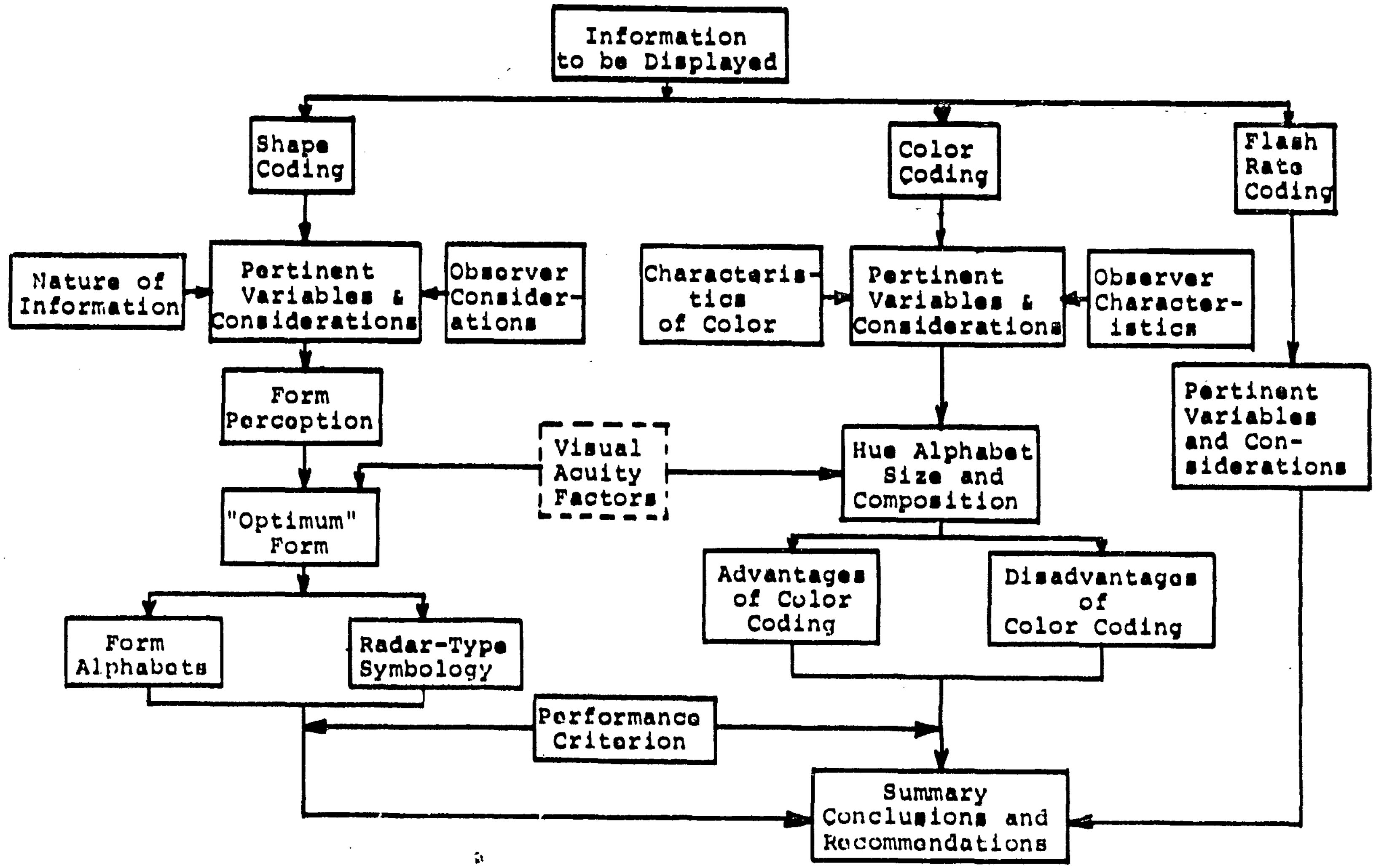


Figure 4. Model of Information Coding Considerations.

Alphanumeric Considerations

The many factors involved in the selection of an optimum alphanumeric for use on electronic displays are shown in Figure 5. There are, however, two principal areas of consideration which ultimately merge together in the rationale for designing alphanumerics. The first area involves general environmental factors such as conditions and orientations of viewing, symbol generation techniques and resolution factors of the display system. Initial consideration should be given to the environmental factors of vibration, acceleration and ambient illumination. Once the effect on legibility of these factors is determined or approximated, an examination of edge displayed symbology (applies if CRT symbology is presented on the periphery of the tube), symbol blur, viewing angle, symbol brightness and symbol contrast percentage (including contrast polarity) should be conducted so the total cumulative effects on legibility may be determined in relation to the symbol generation technique and resolution characteristics of the display system.

The second area involves the selection of a specific font or style and the particular symbol height, proportion (width to height and stroke width to height) and spacing necessary to optimize legibility in relation to the performance requirements of the systems task. Symbol size is the alphanumeric characteristic primarily used to compensate for the legibility degradations imposed by all of the previously mentioned conditions, although many other design trade-offs are possible including contrast, brightness, resolution, etc.

The above flow is presented as a probable course of design consideration, but should not be construed as the only approach. Any of the conditions listed may be individually or collectively altered to adjust legibility.

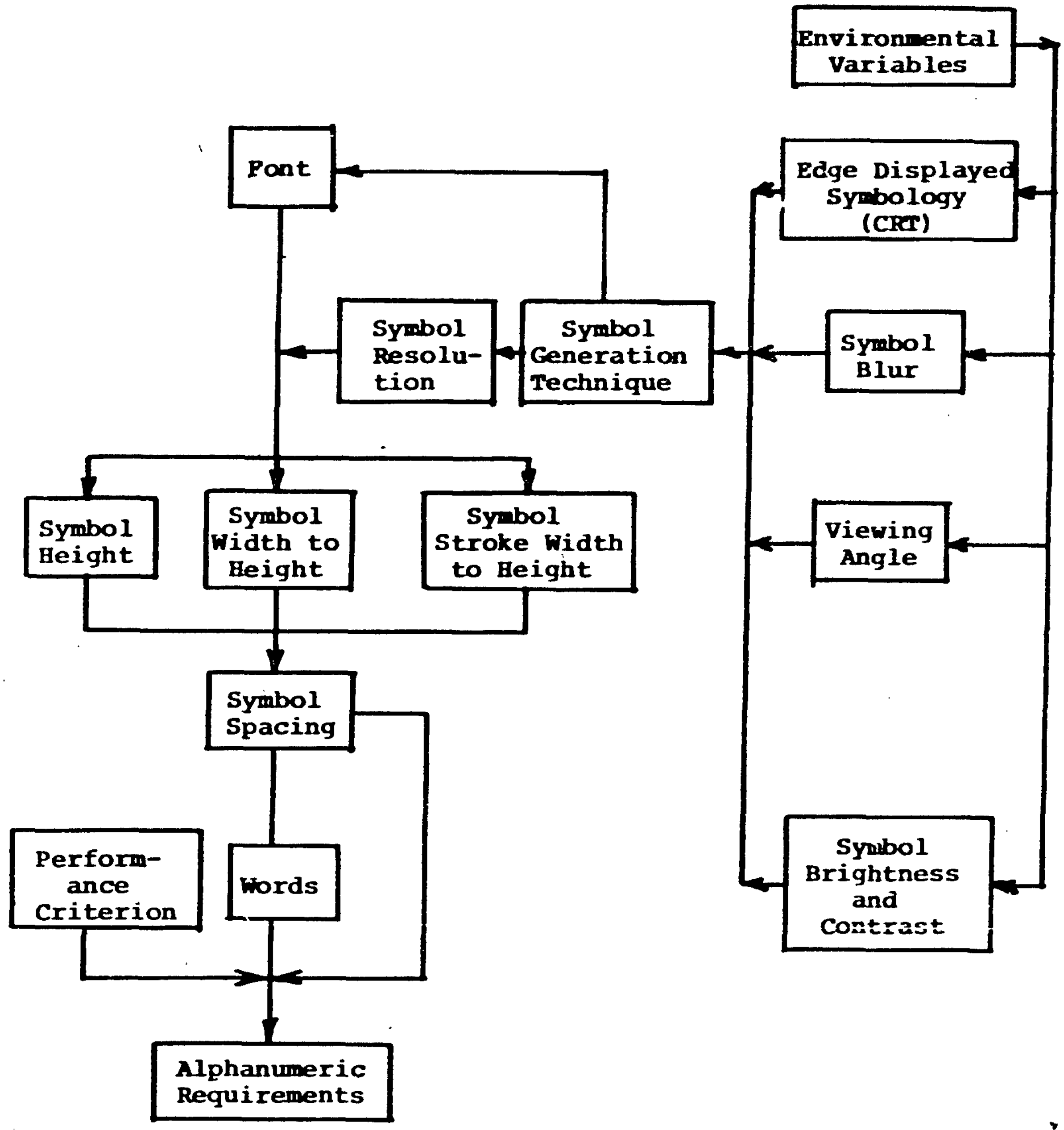


Figure 5. Model of Alphanumeric Considerations.

Scale Legibility Considerations

Scales are components of displays used to present quantitative information, generally either by the movement of a pointer or index relative to the scale, or by the movement of the scale in relation to a fixed readline or fiducial mark. Figure 6 shows the relationships of design variables influencing the precision with which scales can be read.

A primary determinant of scale design is the mission-imposed degree of accuracy with which the scale must be read. In conjunction with this factor are limitations on scale length and consequent requirements for scale value interpolation as opposed to simply reading the scale to the nearest graduation mark. A third fundamental factor involves the selection of scale shape. Fundamentally, scales can be circular (or semi-circular), straight and horizontal, or straight and vertical. Experimental evidence shows that, for a given reading accuracy requirement, design characteristics may vary as a function of the three scale shapes.

Several design considerations are common to all types of scales. These include scale linearity; logarithmic or other nonlinear scales sometimes are encountered, and reading accuracy will vary as a function of the portion of the scale being read. The numbering scheme for scale graduations and major intervals also is of considerable importance, in that improper interval numbering can make an otherwise well designed scale highly error producing. The distance between scale graduation marks and the pointer or readline against which the scale is read also is significant in that excessive distances also will degrade the accuracy with which an otherwise good scale can be read. Of course, scale factor (the distance between major scale graduations) and the number of graduations used are key determinants of scale legibility. Also involved in this area are the stroke width and length of major and minor graduation marks. Finally, checkreading cues designed integrally with the scale can enhance the identification of predetermined scale values. All of the above factors must be considered for proper scale design.

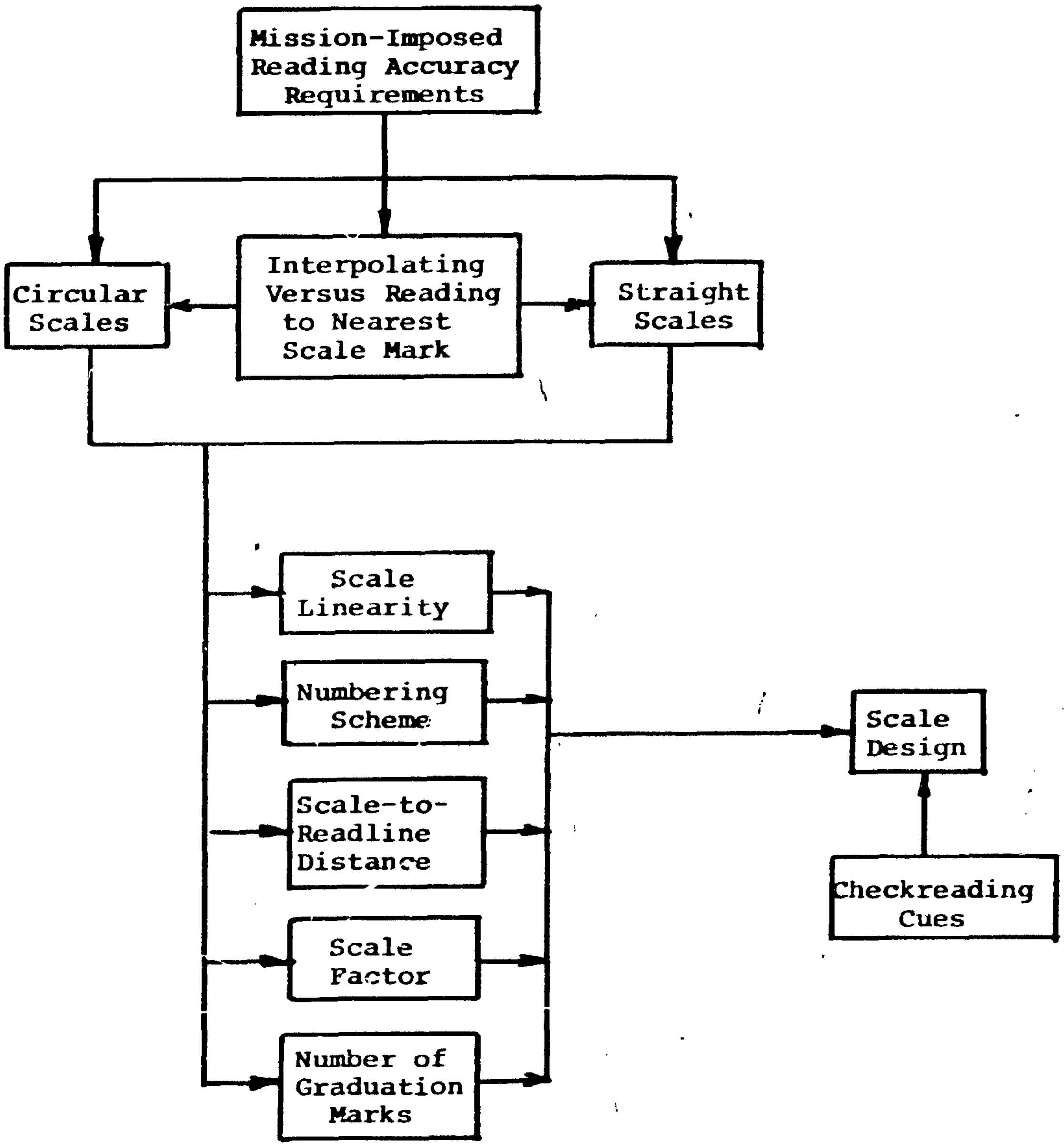


Figure 6. Model of Scale Legibility Considerations.

Factors Affecting Visual Acuity

Visual acuity is defined as the smallest unit discernable by the eye. Minimum discernable acuity is directly affected by a number of environmental and observer parameters as shown in Figure 7. Representative environmental factors include: (1) luminance levels (ambient, surround, display background), (2) spectral composition of luminance, (3) contrast resulting from luminance, (4) duration of luminance flashes or exposure. Environmental factors in turn affect: (1) observer eye adaptation level, (2) nature and extent of optical aberration, (3) the retinal area stimulated, and (4) dynamic acuity. The interaction of all of these factors ultimately determine maximum visual acuity. In addition to the above considerations, other environmental factors (vibration, acceleration, visual time-sharing) and observer factors (fatigue, stress, task overloading) tend to indirectly reduce acuity.

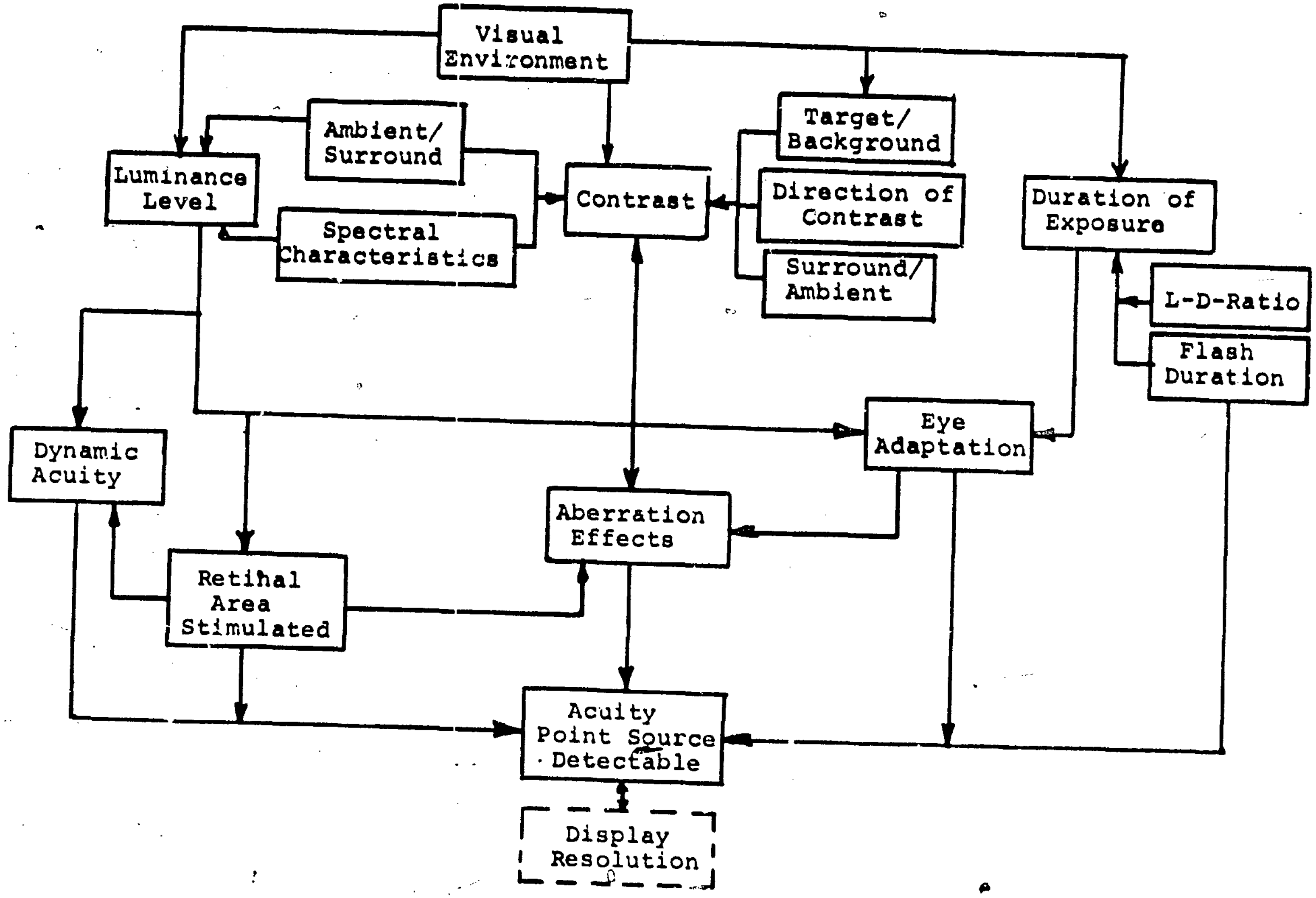


Figure 7. Model of Factors Affecting Visual Acuity.

Display System Resolution Considerations

Resolution is the end product of the interaction of a number of display system parameters as shown in Figure 8. In raster-written displays, resolution is expressed as the number of active scan lines per unit of symbol or display height. Raster lines are composed of a number of "spots", which are the smallest discernable unit of emitted luminance. Representative parameters affecting final spot size include: (1) luminance intensity of system - this parameter interacts with all major components in the system and ultimately determines the scanning beam intensity and consequently the beam diameter, (2) spot spread function - the interaction of the original object point source of light with system (point spread function) in transmission to the display screen, (3) display characteristics - the interaction of system and screen parameters (deflection technique, voltages, phosphor characteristics, halation, tube size, screen efficiency), (4) channel bandwidth - bandwidth capacity (interacting with other system components) directly affects displayed spot size.

Resolution of symbology displayed on CRT screens is generally expressed as the number of raster lines per symbol height. The number of scan lines required for 100% legibility is a function of: (1) the type of symbology displayed, (2) the environmental conditions under which it is viewed, (3) observer viewing distance, and (4) the nature of the observer's task requirements. Signal bandwidth also is important.

Solid-state display resolution is likewise the end product of system parameter interaction. However, no definitive measure of solid-state resolution is commonly used. Representative parameters affecting solid-state resolution include the display emitter size, shape, density, and emitted luminance intensity and hue.

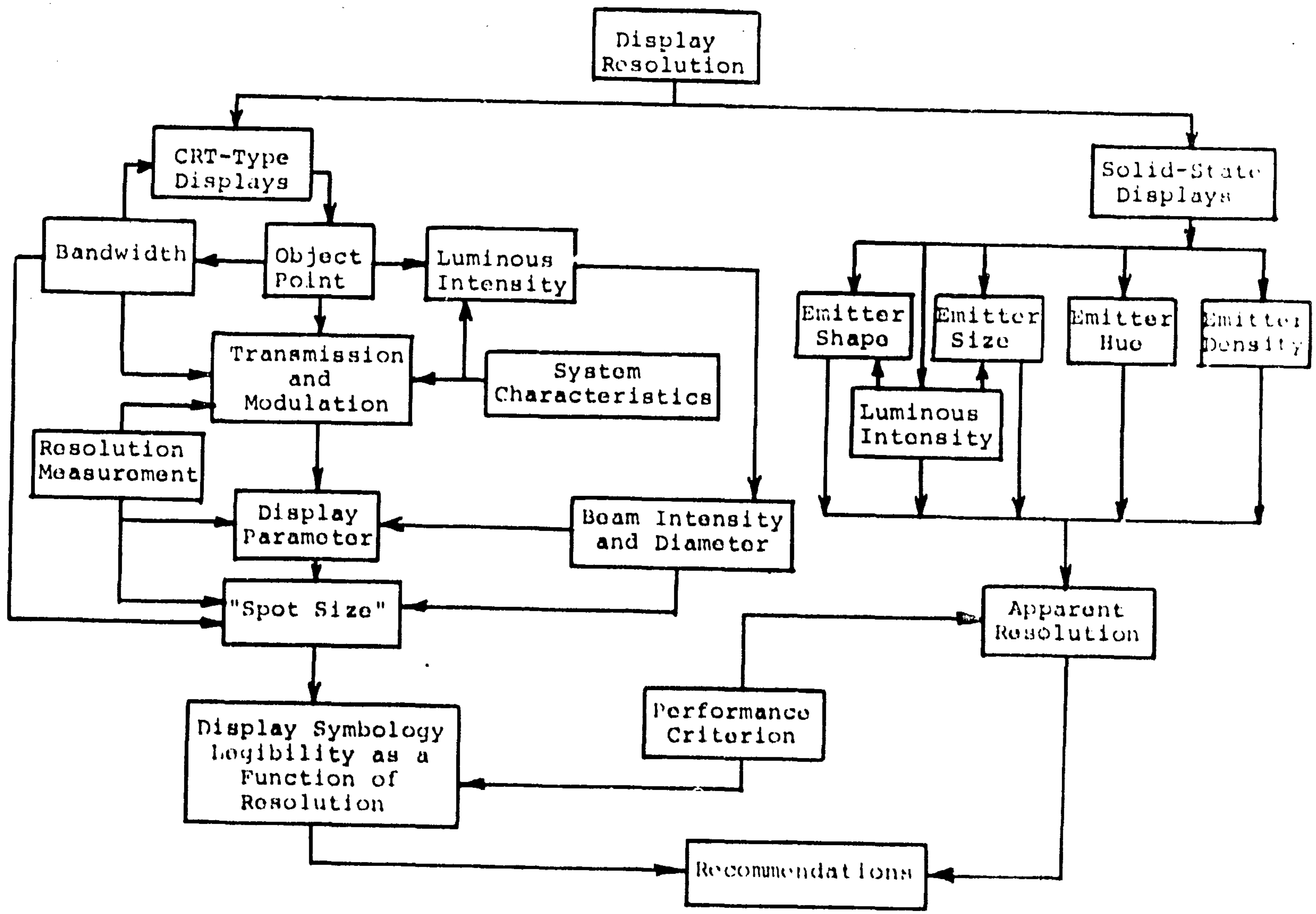


Figure 8. Model of Display System Resolution Considerations.

Flicker Considerations

As shown in Figure 9, factors contributing to the detection of flicker on a visual display may be grouped into two categories: observer and display. Representative observer characteristics that interact to influence flicker perception include: (1) the adaptation level of the eye (affected by ambient and emitted display luminance), (2) "persistence of vision" (affected by the emitted luminance intensity, flash duration and light-to-dark ratio), and (3) the retinal area stimulated (affected by viewing distance, display size and luminous intensity).

Primary display parameters affecting flicker include: (1) phosphor characteristics (decay and emission qualities - which, in turn, affect emitted luminance and refresh rate), (2) display refresh rate (which is, in part, determined by the addressing technique used and phosphor decay functions), (3) information up-date rate (which is affected by the type of information, display refresh rate and the size of the display). All of the above parameters interact, and some tradeoff is possible among the parameters to prevent flicker on the display. In any event, it is essential to have a flicker-free display.

Flicker Considerations

As shown in Figure 9, factors contributing to the detection of flicker on a visual display may be grouped into two categories: observer and display. Representative observer characteristics that interact to influence flicker perception include: (1) the adaptation level of the eye (affected by ambient and emitted display luminance), (2) "persistence of vision" (affected by the emitted luminance intensity, flash duration and light-to-dark ratio), and (3) the retinal area stimulated (affected by viewing distance, display size and luminous intensity).

Primary display parameters affecting flicker include: (1) phosphor characteristics (decay and emission qualities - which, in turn, affect emitted luminance and refresh rate), (2) display refresh rate (which is, in part, determined by the addressing technique used and phosphor decay functions), (3) information up-date rate (which is affected by the type of information, display refresh rate and the size of the display). All of the above parameters interact, and some tradeoff is possible among the parameters to prevent flicker on the display. In any event, it is essential to have a flicker-free display.

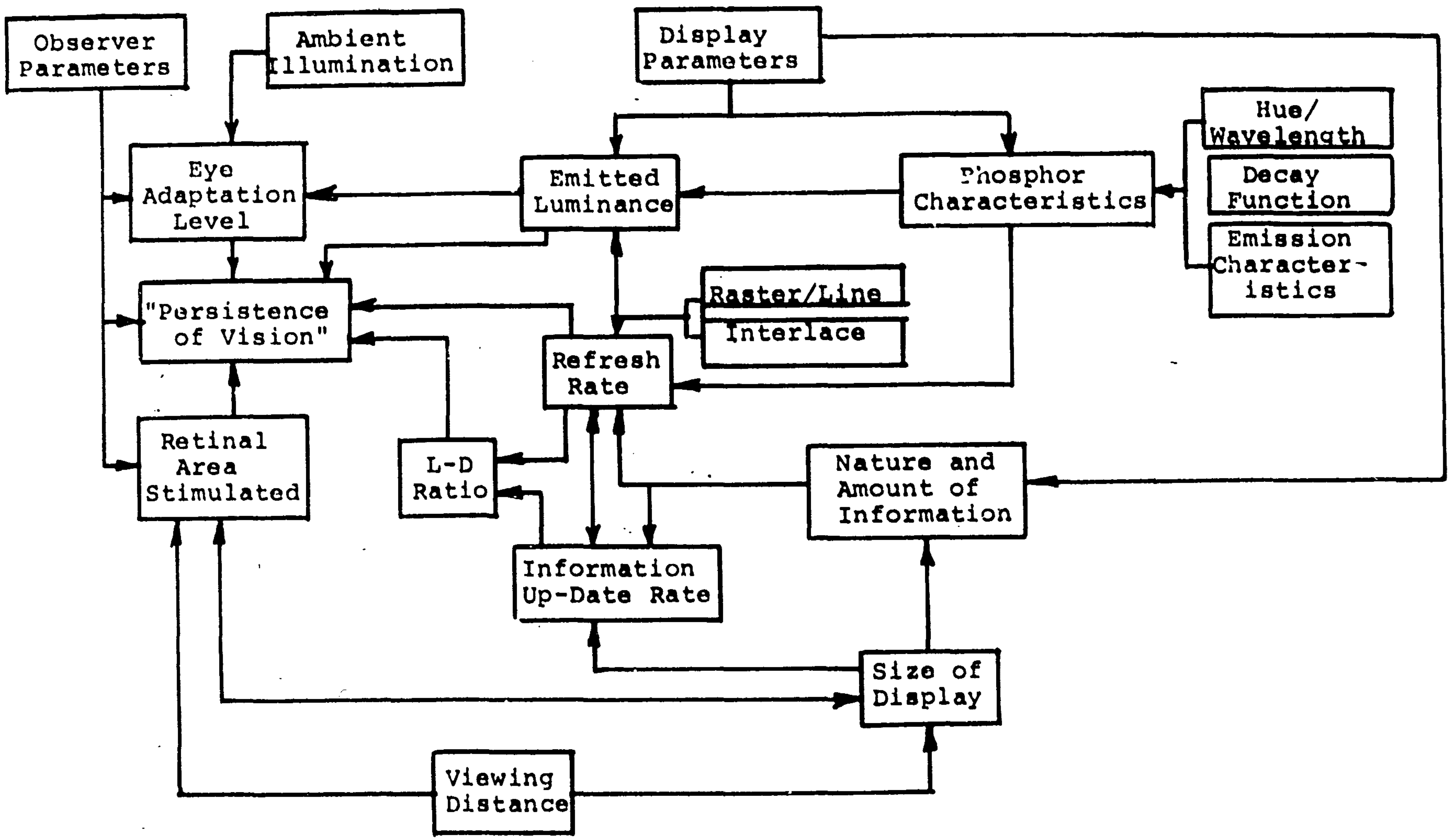


Figure 9. Model of Factors Influencing Flicker.

Legibility Contrast Considerations

To be legible, electronically generated symbology must be sufficiently brighter than the immediately surrounding display background to ensure that the symbols will stand out. Figure 10 shows the relationships of factors influencing symbol brightness and contrast requirements.

There is no one contrast ratio which will satisfy all symbol luminance requirements in relation to display background luminances. As display background luminance increases, symbol luminance also must increase, but not in direct proportion to display background luminance.

Four fundamental families of considerations are involved in specifying symbol luminance and contrast. One of the most important involves display background luminance levels with which symbology must compete in order to be clearly legible. Factors of incident illuminance, display reflectivity and display-induced background luminance are involved. The second factor involves symbol luminance and the extent to which the display face and filters may attenuate symbol luminance. Display background luminance and symbol luminance are the key determinants of contrast. A third and significant factor influencing contrast requirements involves symbol size and shape, since smaller and less solid symbols require greater contrast for legibility. Operator performance expectations also combine with symbol dimensions in specifying minimum contrast required. For example, contrast requirements increase as performance requirements become more stringent, such as mere legibility, versus legibility with minimum reading time, versus comfortably bright and contrasty symbology. Finally, symbol contrast requirements are influenced by the luminance level to which the pilots eyes are adapted. There also is some evidence that the use of sun visors or sun glasses may influence contrast requirements, not only because of their effects upon eye adaptation, but also for other reasons which have not yet been fully examined.

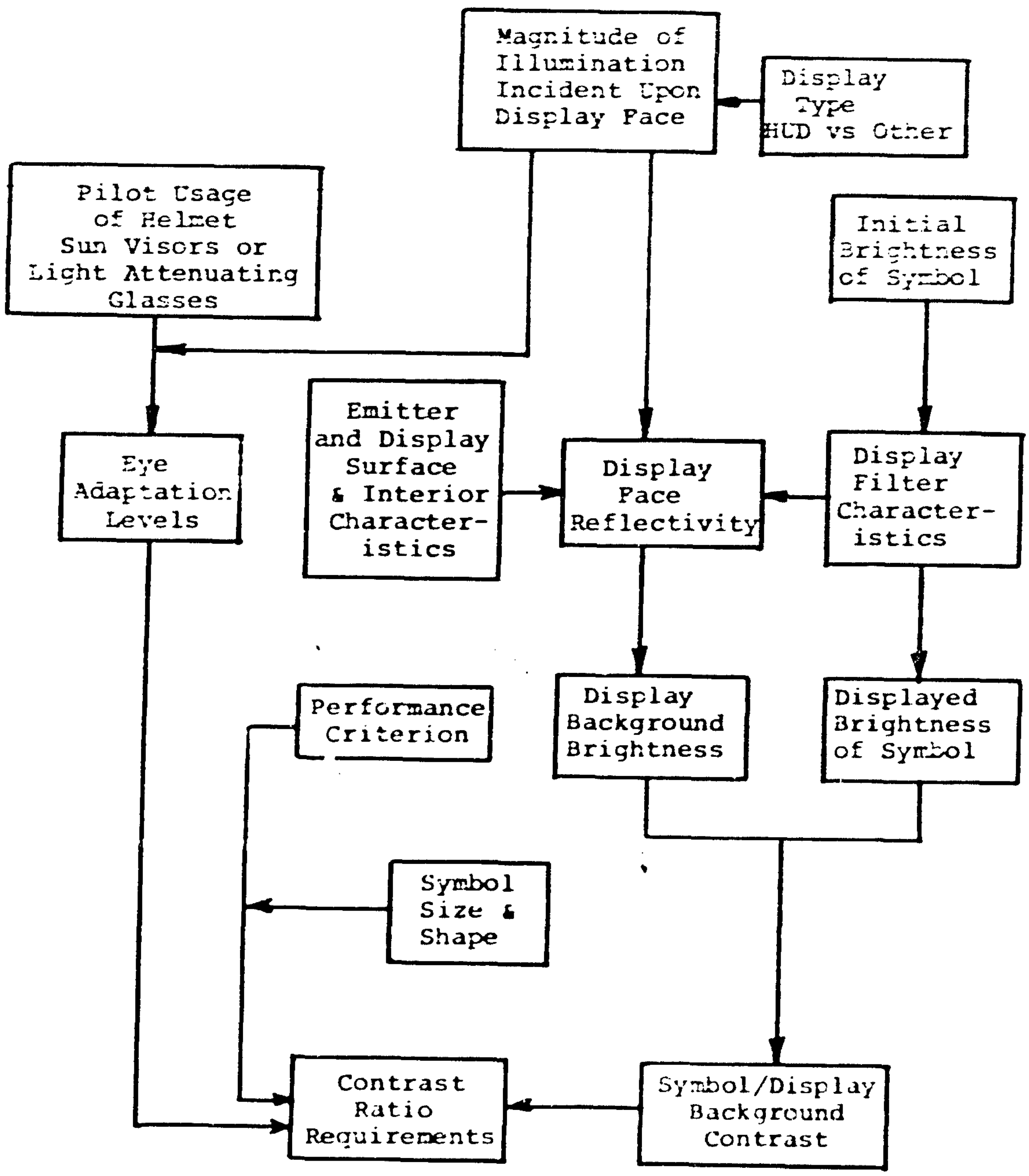


Figure 10. Model of Considerations Affecting Legibility Contrast Requirements.

Environmental Variable Considerations

Environmental variables affect all legibility, readability and usability considerations and should be considered early in display design planning. Three environmental variables are reported: ambient illumination, vibration and acceleration.

As indicated in Figure 11, ambient illumination affects electronic flight displays as a function of three primary considerations. The first relates the value of solar and atmospheric illumination based on the existing meterological conditions and orientation of the aircraft in relation to the sun. This gross level of illumination is then affected by the second consideration which involves the transmitivity of the aircraft canopy and windscreen and the geometry of the cockpit. Once these factors have influenced the incident illumination, the third factor, which is the display location, must be considered before a final ambient illumination level can be determined at the display face.

The factors which must be considered when accounting for the effects of vibration and acceleration on display legibility are very similar. The initial consideration for vibration involves the frequency in cycles per second or hertz, whereas for acceleration first throughts are given to the rate of onset (in g's/sec.). When these factors are determined, deliberation must be given to the amplitude (which is an expression of the force magnitude in g's) and duration (in seconds) parameters of both vibration and acceleration. Also common to both vibration and acceleration are considerations of the force vectors through the human body. Primary emphasis in this review has been given to z-axis vibration and x-axis acceleration. When examining forces in relation to the body, it is also necessary that the relationship of the body to gravity be specified, for example, whether the subject is in a normally seated position, in a semisupine position, etc. The last of the considerations for vibration and acceleration is the type of restraint system used. This section does not attempt to review the merits of various experimental restraint systems since our emphasis is toward specifying design parameters appropriate to both normally seated and restrained aircraft pilots. Inherent in restraint systems are considerations of whether or not subjects were wearing g-suits (applies more particularly to acceleration).

Common to all environmental variables are delineations of the operator task and performance requirements.

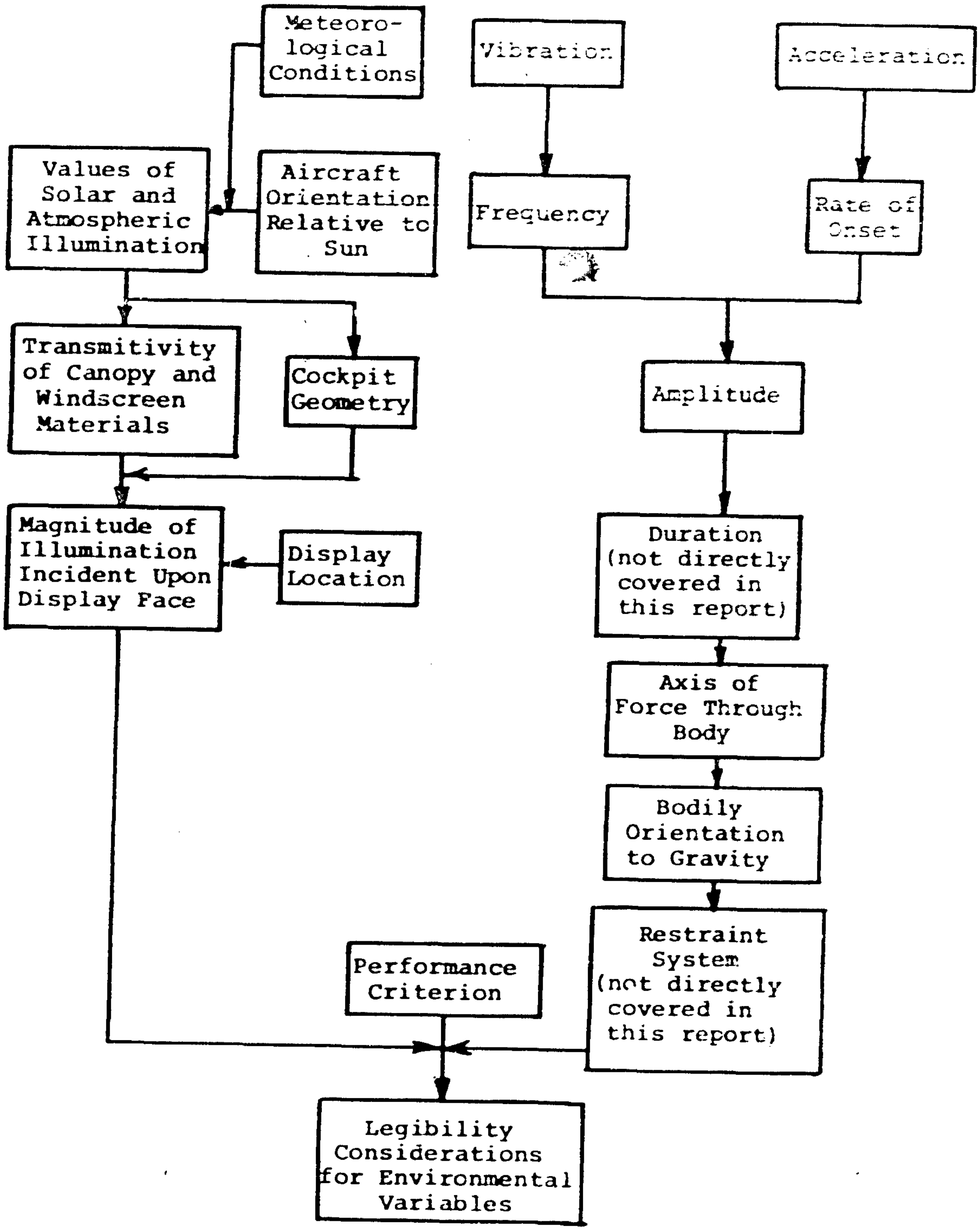


Figure 11. Model of Environmental Variable Considerati .

SECTION III

DISPLAY SIZE FOR FLIGHT CONTROL

INTRODUCTION

Current and projected cockpit designs are increasingly incorporating multiple electronic displays for flight control, navigation, weapon delivery and reconnaissance. One of the arguments for the use of multiple electronic displays involves reliability. Should one display fail, needed information can be presented on one of the remaining operative displays. Whether designing electronic flight displays for special use or for timesharing usage, the designer must consider display requirements for each task for which the electronic flight display may be used. One consideration which frequently is not given objective and detailed consideration is display size.

Assuming that the numbers of vertical and horizontal display resolution elements remains unchanged by varying display size, changes in display size, either in conjunction with sensor field of view or independently of sensor field of view, will affect image quality, display flicker, and human performance. The changes in human performance may be in part due to changes in image quality; on the other hand, they may be quite independent of this factor. Direct effects of display size and sensor field of view are discussed below as they influence measures of target detection performance and human operator continuous control performance.

Display size produces markedly different effects upon target detection and continuous control performance. Generally speaking, increasing display size reduces the probability of detecting targets on either PPI type presentations or radar imagery-type presentations. It is to be anticipated that similar effects would be observed for low light-level television although this remains to be confirmed. With tasks involving flight path control and the use of artificial horizon or flight director displays, increasing the size of the displays can influence tracking or flight control performance. The effects are fairly complex; however, all effects appear to be quite small, thus giving the designer considerable flexibility.

It is to be anticipated that vehicle dynamics will interact with display size to influence pilot continuous control performance. This latter interaction, of course, can be due in large part to the effects which varying display size may have upon scale factors associated with display elements. This, of course, depends upon whether scale factor is controlled independently of display size. The effects of task and display

size upon target detection and continuous control performance are discussed separately below.

TARGET DETECTION TASKS

Within this discussion, the effects of display size, signal-to-noise ratio and pip or target size are briefly discussed as they influence the probability that the operator will detect bonified targets. Probability of detection is not the only measure used to define target detection performance. Other measures include: frequency of false-positive identifications, wherein non-targets are identified as targets; weighted measures of performance in which number of target identifications is weighted against number of false positives and number of targets missed; and target detection times. This review deals only with probability of detecting bonified targets, and is intended primarily to show that the effects of display size vary as a function of operator task.

It would appear that the effects of display size upon target detection performance are not well recognized. In a recent review of the literature dealing with operator-reconnaissance display system performance, Semple and Gainer (Ref. 294) found that investigations of the effects of many other variables upon detection performance totally ignored display size as a variable. Semple and Gainer also report that noting the sizes of displays used in numerous studies which were reviewed provided a curiously accurate means of predicting maximum probability of target detection performance, at least for studies involving radar imagery or incorporating other factors such as display noise or clutter in addition to target symbology.

Noise

Assuming that information density, scale factor, target contrast and target size factors are held constant, a review of the literature showed that variations in display size had no meaningful impact upon probability of target detection for noise-free display presentations. This trend held for display sizes (diameters) ranging from 0.20 inches to 15 inches.

The addition of symbology, information, or noise over and above target information has a marked impact upon probability of target detection for displays larger than only 0.75 inches in diameter. Data from Meister and Sullivan (Ref. 232) and Weasner (Ref. 342) were combined to generate Figure 12. Data presented by Weasner covered display diameters from 0.20 inches through 6.0 inches. Data published by Meister and Sullivan covered display diameters from 3.0 through 14.0 inches. Probability of detection data matched remarkably well (within a few percentage

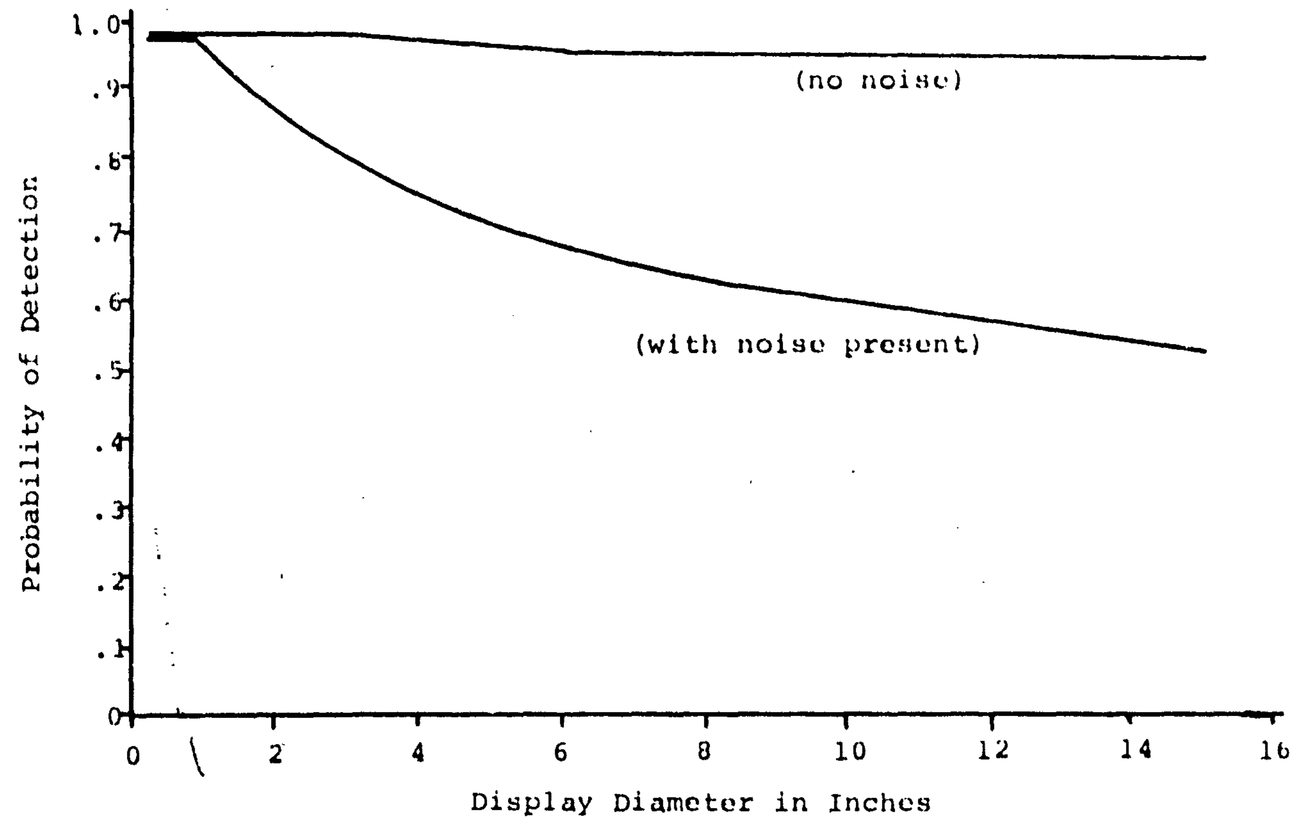


Figure 12. Probability of Target Detection on a PPI Display as a Function of Display Size and Noise.

points) at the six inch diameter. Trends of the curves from the two sources also are well matched.

Pip Size

Within the context of plan position indicators (PPI) displays, pip (symbol) size interacts with display size to influence target detection. Meister and Sullivan have reviewed the literature on this subject. They note that a frequent human factors handbook recommendation for CRT size is seven inches of diameter. They point out that this recommendation is based upon PPI data and assumes smaller target pip sizes of two to eight millimeters for approximately 14 inch viewing distances. When larger target sizes are involved (e.g., 12 to 16 mm), the advantage of the seven inch scope becomes less. For larger target sizes, 17.5 to 18 inch scopes frequently are recommended. The tradeoff, however, really lies between pip size and display size. Typically, radar target detection, for example, improves as pips get larger up to about 60 minutes of visual angle, but decreases continually as the scope becomes larger.

Meister and Sullivan report a regression equation which they feel is useful in relating target detection probability to display size and pip size. The equation is:

$$Y = 26.02 + 3.33X - 0.22X^2 - 0.46XZ + 2.09Z$$

where: Y = mean detectability threshold in decibels attenuation of a reference voltage

X = target range in tenths of PPI display radius

Z = usable display diameter in units of 7 inches.

Radar Imagery

A somewhat different approach to the problem of display size is to vary sensor field of view in conjunction with display size. The approach has particular application for considerations relating to the display of high resolution radar imagery.

Fundamentally, sensor field of view and display size can be related to human target detection performance through imagery scale factor and display size. For example, if display size is decreased while sensor field of view is held constant, the result is a reduction in scale factor of the displayed information because the same amount of information must be presented in a smaller area, requiring a reduction in scale factor (the relationship between inches of display dedicated to displaying inches of real-world content).

Simon (Ref. 367) has reported a study of target recognition using simulated aerial reconnaissance radar imagery in which the simulated sensor field of view was, under certain combinations of conditions, held constant, while display size was varied. Six and 12 inch display sizes were used. With the sensor fields of view studied, the corresponding display scale factors were 1:216,000, 1:108,000 and 1:54,000. Observers were allowed either 10, 20 or 40 seconds viewing time and were asked to recognize targets such as airfields, tank farms and a stadium.

In analyzing the resulting data, Simon did not take into account the fact that imagery scale factor was being varied simultaneously with display size and sensor field of view. Simon's data have been replotted in Figure 13 in a manner which allows both display size and imagery scale factor to be related to probability of target recognition for each of the three viewing times studied. Inspection of Figure 13 reveals that display size, imagery scale factor and viewing time all have marked impacts upon target recognition performance.

It can be seen from the figure that the effects of display size can be directly compared at the 1:108,000 scale factor. Examination of the figure shows that performance with the 12-inch display was inferior to performance with the six-inch display at this scale factor. It is further apparent that performance with the 12-inch display at the 1:108,000 scale factor was not much better than performance with the six-inch display at the much higher scale factor of 1:216,000. If one linearly extrapolates the six-inch display curve to the 1:54,000 scale factor, it would appear that the 12-inch display should produce performance comparable with the six-inch display. It would seem, therefore, that the effects of display size upon probability of target detection are fundamentally similar whether PPI or imagery presentations are involved. Smaller displays result in higher probabilities of target detection.

CONTINUOUS CONTROL TASKS

Introduction

One of the primary displays likely to be found in cockpits of future aircraft will be the Electronic Attitude Director Indicator (EADI). A related display used for head-up flightpath control and weapon delivery will be the Head-Up Display (HUD). With very few exceptions, symbology for these types of displays is electronically generated, thereby allowing for considerable latitude in selecting display sizes and information scale factors (sensor field of view considerations).

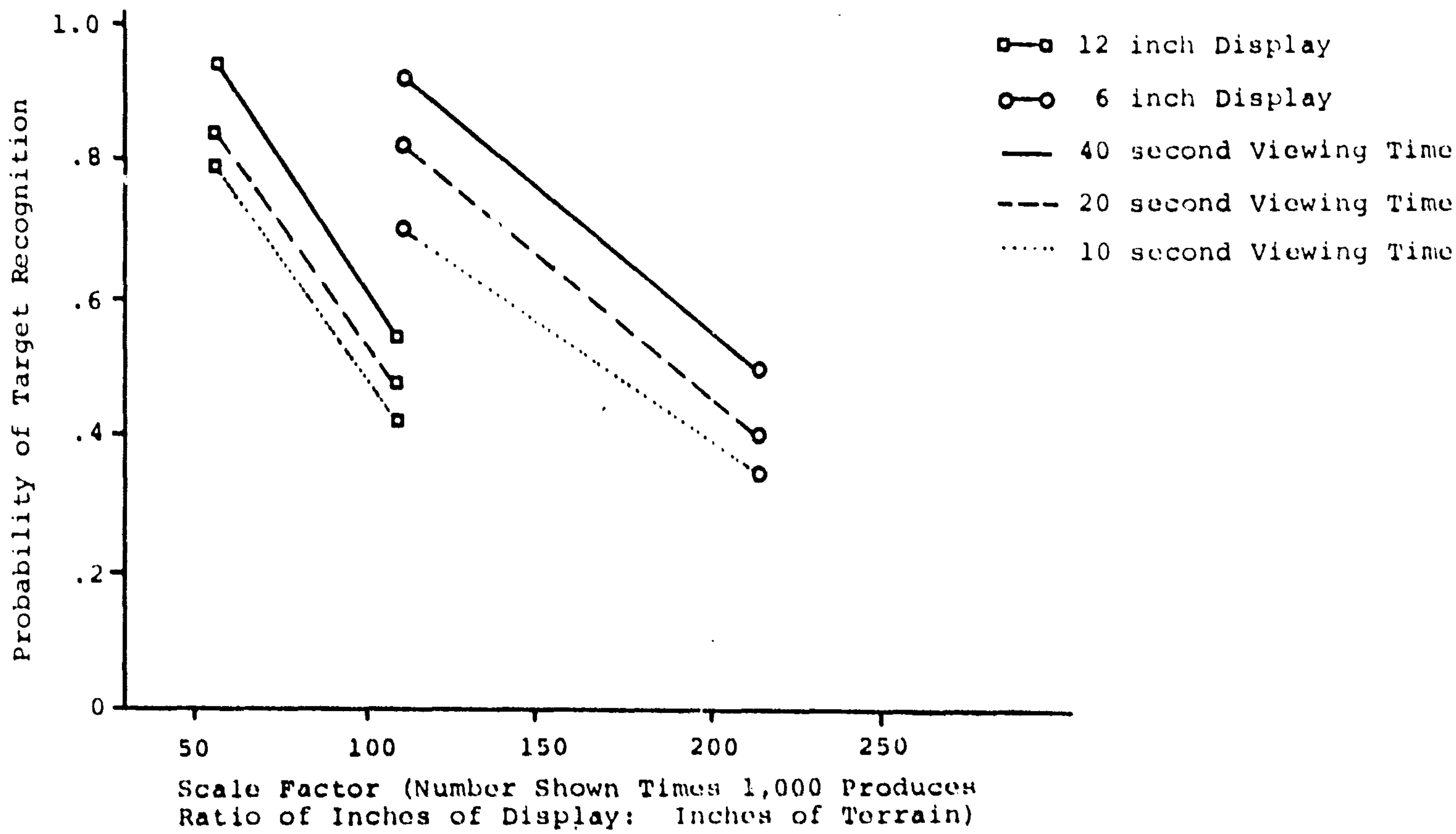


Figure 13. Probability of Target Identification from Radar Imagery as a Function of Display Size and Scale Factor. (Adapted from Simon, Ref. 367)

EADI's and HUD's can contain a variety of different types of information presented in several ways. For example, Ketchel and Jenney (Ref. 206) reviewed current and proposed display designs and conclude that, in relation to real-world counterparts, scale factors for pitch, roll and heading information range from 1:1 to 1:6, which is a sizeable range. Additionally, overall sizes and shapes of electronic flight displays are not consistent. Benjamin (Ref. 26) reports that the EADI for the Navy F-14 aircraft will be a square display measuring approximately five inches on each side. Other EADI's which have been designed or flown have, on occasion, been larger, with some exceeding nine inches in diagonal dimension. Finally, the aspect ratios of all EADI's are not square. Width frequently exceeds height by factors of 1.1 to 1.4. Similar trends may be identified for HUD's, although aspect ratio for these displays generally is unity.

Because of variations in overall size, aspect ratio (height-to-width) and information scale factors, and because display dimension variations are known to affect both picture quality and human performance measures, it is both realistic and timely to examine the effects which such variations may have upon continuous control performance.

Design Variable Relationships

As with radar or other imagery-type displays, both display size and scale factor (sensor field of view) may be anticipated to influence continuous control performance. With EADI's or HUD's, either variable may be changed independently of the other. In other instances, however, simply expanding display size may serve to automatically increase scale factor, even though sensor field of view is held constant. An example is the display of bank angle information. As display width is increased, the bank angle scale factor may be considered to increase, primarily because the horizon line will now extend a greater distance from the display center, resulting in the extremes of the line traveling greater distances for each degree of bank angle change. Applying the converse of the argument, if sensor field of view is held constant, reductions in display size will produce corresponding reductions in pitch bank and heading scale factors. It certainly would not be impossible to reduce display size to the point where continuous control performance would diminish simply because the resulting scale factor would be insufficient to allow for necessary scale reading accuracy. Accordingly, precision of continuous control tasks would diminish, although the degree of degradation most certainly would be influenced by system (aircraft and controller) dynamics.

It is unlikely that there is one display size, aspect ratio or information scale factor which will result in optimum continuous control performance for all system and controller dynamics. It is likely that the effects of display size, aspect ratio and scale factor will vary as a function of the information content of the display and the pilot's task. For example, if the pilot's task involves the compensatory tracking of properly quickened and scaled steering commands, it is unlikely that other display dimension variables will have a marked impact upon his performance. However, this is not to suggest that quickening removes requirements for the proper design of other display elements. Vreuls et al. (Ref. 372), for example, have shown that the use of either expanded localizer symbols or rising runway symbols (radar altitude) can enhance touchdown performance during simulated Category III-C (zero visibility) landings. However, combining the expanded localizer and rising runway information into one symbol which moved both vertically and laterally in response to input signals produced touchdown performance which was inferior to that obtained when neither rising runway nor expanded localizer was present. These statistically significant findings were obtained even though the pilot's (apparently) primary task was the compensatory tracking of integrated, quickened command steering symbols. It is apparent, therefore, that pilot task and other EADI content influence display dimension requirements, and most certainly influence research findings.

For flying tasks not involving the use of quickened steering commands, it is to be anticipated that display size, aspect ratio and scale factor will play more significant roles in aircraft control. It is also to be anticipated, however, that mission requirements (e.g., level flight, terrain avoidance or airborne weapon delivery) also will have meaningful impacts upon EADI or HUD design. Finally, the effects of aircraft and controller dynamics certainly will be influential, as will environmental factors such as turbulence.

It is not the objective of this review to attempt to specify the characteristics of an optimum or universally applicable EADI or HUD display. Rather, relevant research is reviewed so that variables of established impact can be identified and the nature of their effects and interactions documented for future consideration. Indeed, as many human factors engineers and display design engineers have repeatedly pointed out, it will probably be necessary to verify display design through simulation or inflight testing. Because of the numerous variables involved in the man-machine interaction related to continuous control tasks, it is likely that this necessity may persist for many years to come.

Research Evidence

Display size and, consequently, pitch and bank angle scale factors have been examined indirectly through the evaluation of alternative designs for electromechanical attitude director indicators (ADI's). It must be remembered, however, that indirect comparisons can provide only indirect information because numerous other display features also are involved. For what it may be worth, however, Monroe, Vreuls and Semple (Ref. 244) present a summary of a study by Gainer et al. (Ref. 124) in which instrument approach and landing performance was investigated as a function of attitude director indicator design. Two smaller, four-inch ADI's (Sperry HZ-4 and Bendix 300) were contrasted with two larger, five-inch ADI's (Sperry HZ-6 and Collins FD-109). Forty commerical aviation and military pilots flew a total of 1,920 simulated ILS Category III-C approaches and landings in a multi-jet simulator representing the Boeing 707 aircraft. All approaches were initiated at 2,500 feet altitude and 12 miles from the simulated glideslope transmitter. In addition to types of flight director displays, cross wind conditions and altitudes at which autopilot failures occurred also were systematically varied and tested. All approaches started with the autopilot in the coupled mode. During each approach autopilot failures were separately introduced in both the pitch and roll axes in order to require the pilots to manually fly the simulator using the various ADI's. At touchdown, pilots always were in full manual control of all axes. Both objective system performance data and pilot opinion data were collected and analyzed. Representative measures of touchdown performance included: runway range, centerline deviation, roll attitude, pitch attitude, heading error, airspeed, vertical velocity and drift rate. Analysis of the data showed that 34% of the touchdowns were successful with the smaller displays, while 50% were successful with the larger displays. It is quite obvious that all of the displays had been tested beyond their design limits. However, the larger displays did produce somewhat better performance. Pilot preference also favored the larger displays.

Roscoe, Hasler and Dougherty (Ref. 284) have recently reported a study conducted in 1951 to investigate the proficiency with which pilots could make takeoffs and landings using a periscope as the only source of outside visibility. Using a twin-engine Cessna T-50, six military pilots flew take-offs, complete traffic patterns and spot landings. The aircraft's artificial horizon was covered; glideslope and localizer displacement displays were not used. The pilots' only attitude and position reference to the outside world was by means of a projected periscope display.

Roscoe et al. cite a preliminary study by Roscoe (Ref. 281) involving measurement of the precision with which pilots controlled the attitude of an aircraft while performing standard

instrument flight patterns. Size of the projection periscope display area and the field of view of the sensor optics were varied. Although no data are presented, Roscoe et al. report that results of the experiment clearly indicated that the precision with which pilots could control the attitude of the aircraft using the pictorial display improved significantly with increases in the size of the display size up to eight inches by eight inches. They also report that wider angles of horizontal visibility associated with lower image magnifications resulted in greater precision in the pilots' control of aircraft attitude in horizon-reference maneuvers (e.g., rated turns, climbs, descents and combinations thereof).

In the experiment reported in Ref. 284, Roscoe et al. varied the magnification (i.e., the scale factor) of the projected periscope display. The display was mounted at the windscreen directly in the pilot's line of sight. Viewing distance was 15 inches. When viewed from this distance, the viewing screen subtended a monocular field of view of 30 degrees. Consequently, if a 30-degree outside angle was included in the eight inch by eight inch image, the resulting magnification (scale factor) was one. By making alterations to the sensor field of view, scale factors of 0.86, 1.20 and 2.00 were achieved for investigation. In addition to collecting touchdown data for the three scale factor conditions, data were recorded for visual contact landings in order to provide a baseline.

Two measures of performance were recorded by Roscoe et al. The indices of safety was simply the number of times which safety pilots had to assist pilots in making takeoffs or landings. These numbered only four out of 120 takeoffs and landings, and were not analyzed further. Assuming sufficient training, the authors concluded that the safety of periscope flight had been demonstrated. The index of accuracy of landing was the difference in feet between the point of landing and the desired landing spot. Touchdown accuracy data were analyzed to determine the influence of different image scale factors (magnifications), the effects of practice, and the effects of using the periscope in comparison with contact landings. Figure 14 presents distributions of touchdown errors for each of the scale factors and for contact landings. Figure 15 shows variability of touchdown errors as a function of practice and display conditions.

Mean touchdown errors were found to be a simple inverse linear function of image magnification within the range of magnifications studied. In comparison with perfect touchdown performance (zero error), the 0.86 magnification resulted in an average 72 foot overshoot. The difference was statistically significant at the .03 level of confidence. The authors attribute the overshoot to the fact that the 0.86 magnification produced an effect somewhat like looking through binoculars

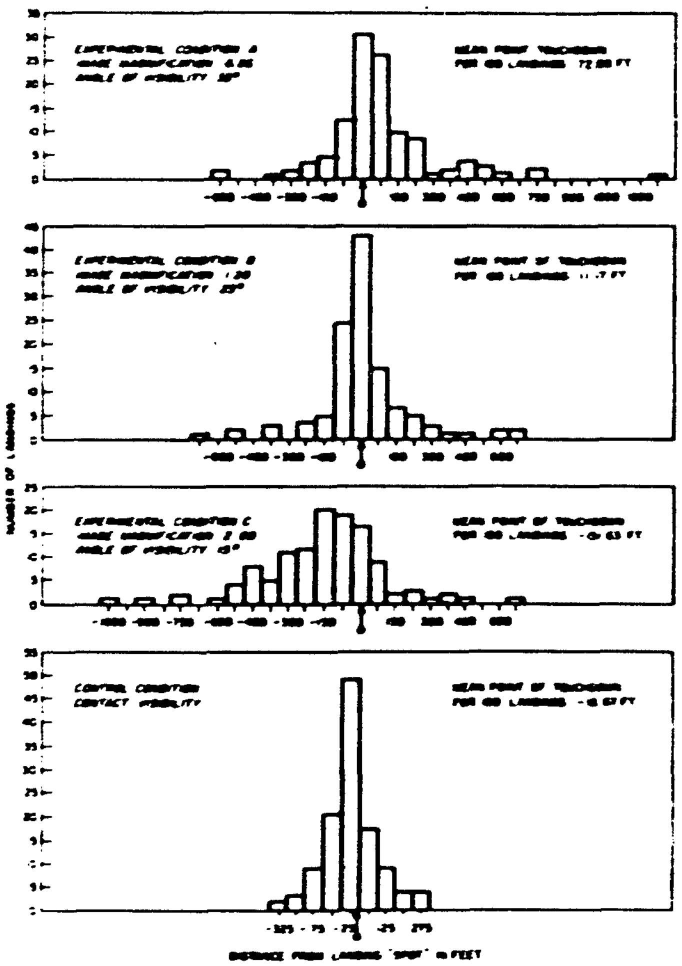


Figure 14. Distributions of Touchdown Points
(Adapted from Ref. 284)

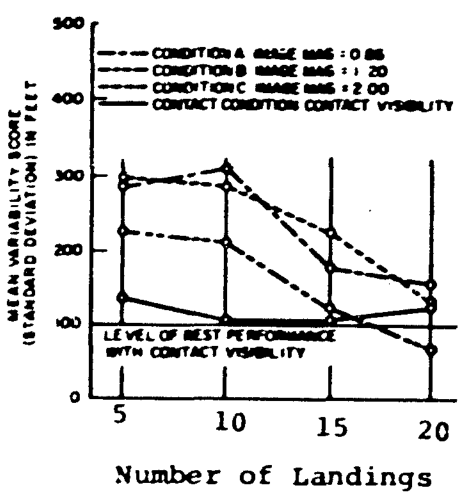


Figure 15. Variability of Touchdown Points as a Function of Practice.
(Adapted from Ref. 284)

backwards; the effect is that objects appear farther away than they actually are. The 2.00 magnification resulted in an average 200 foot undershoot, which was significantly different from zero undershoot at the .005 level of confidence. The effect of the 2.00 magnification was to make objects appear closer than they actually were. Finally, the 1.2 magnification, which caused objects to appear approximately the same distance away as they would when viewed with unrestricted contact visibility, resulted in average touchdown errors which were not significantly different from either zero error or from the average error observed for visual landings. Similar trends may be observed in the variability of touchdown errors as shown in Figure 15. It should be noted, however, that variability of touchdown performance consistently diminished as a function of practice. No statistically significant differences were found among the four conditions during the last block of five landings.

Based upon the results of the studies by Roscoe (Ref. 281) and Roscoe et al. (Ref. 284) it would appear, at least for flight by periscope, that reduced magnification may enhance horizon-reference flight performance, while a magnification factor approaching one is to be preferred for approach and landing performance.

In 1962, Fedderson (Ref. 368) reported a comparison of helicopter hovering performance using eight-inch and a 14-inch contact analog displays. Hovering performance was measured in the Bell Helicopter Simulation Laboratory using a six degree of freedom dynamic platform. No statistically reliable differences were reported for hovering performance as a function of display size. Cross and Bittner (Ref. 97) point out, however, that the hovering task required during simulation trials involving the 14-inch display was more difficult than the hovering task used with the eight-inch display. It is quite difficult, therefore, to draw any meaningful conclusions from Fedderson's study.

Cross and Bittner (Ref. 97) have recently reported experimental data generated using a vertical contact analog display (VCAD). The objectives of their studies were to define the relationship between VCAD display size and the accuracy of judging certain flight parameters, and to obtain estimates of the absolute accuracy with which selected flight parameters could be judged as a function of display size. Using what is described as a general purpose, fixed-base aircraft simulation, experimental subjects were required to make control inputs to adjust VCAD presentations for various pitch angles, roll angles and altitudes. The VCAD displayed only ground plane and sky plane contact analog textures, along with a horizon line. Other contact analog symbology was not used. Control inputs were not aerodynamically crosscoupled; accordingly, for example, changes in roll angles did not produce corresponding changes in pitch

angle, or subsequently, altitude. Manipulations in display size were accomplished by changing the sizes of the CRT's on which the display was presented, while holding viewing distance constant at 32 inches. Four different tube sizes were used (5-inch, 8-inch, 14-inch and 17-inch). Tube dimensions in inches and corresponding visual angle dimensions are shown in Table 2. A 1:1 relationship between display movement and corresponding real-world cues was used for all display sizes. Results of several separate experiments are discussed below:

Table 2. Display Dimensions Studied by Cross and Bittner

Tube Size	Height	Width
5 inches	3.4" (6^{o} 6')	4.5" (7^{o} 58')
8 inches	5.4" (9^{o} 34')	7.0" (12^{o} 30')
14 inches	9.1" (16^{o} 16')	11.9" (21^{o} 4')
17 inches	10.9" (19^{o} 22')	14.2" (25^{o} 2')

Roll angle control was investigated by requiring four non-pilots to maintain pre-specified roll angles in the presence of low amplitude, low frequency forcing functions in the pitch and roll axes. Subjects operated a rate control joystick to maintain roll angles of zero, 20 and 60 degrees. Eight, 14 and 17-inch display sizes were used. Each subject maintained each roll angle for ten two-minute trials using each display size. Results of the experiment showed that subjects were able to maintain all three roll angle standards with very high degrees of accuracy after only a few trials. Maximum error seldom exceeded two degrees, regardless of display size used. Average absolute error averaged over a trial seldom exceeded 0.5 degrees. Root mean square (RMS) error data are plotted in Figure 16 as a function of roll angle and display size. Curves for other display sizes were analytically determined and are shown in the figure.

Two aspects are of signficance in Figure 16. First, all roll angle RMS error values are quite small. Second, it is quite apparent that display size interacted with the particular roll angles which subjects attempted to hold. Cross and Bittner indicate that the causes of the interaction are not totally clear, but may be due in part to difficulty in perceptually integrating over large display areas. Based upon these data, Cross and Bittner concluded that the "optimal" display size is dependent upon the magnitude of the roll angle being judged. If the roll angle standard falls below 18 degrees, larger size displays are favored. If roll angle exceeds 18 degrees, smaller sizes prove better. Considering

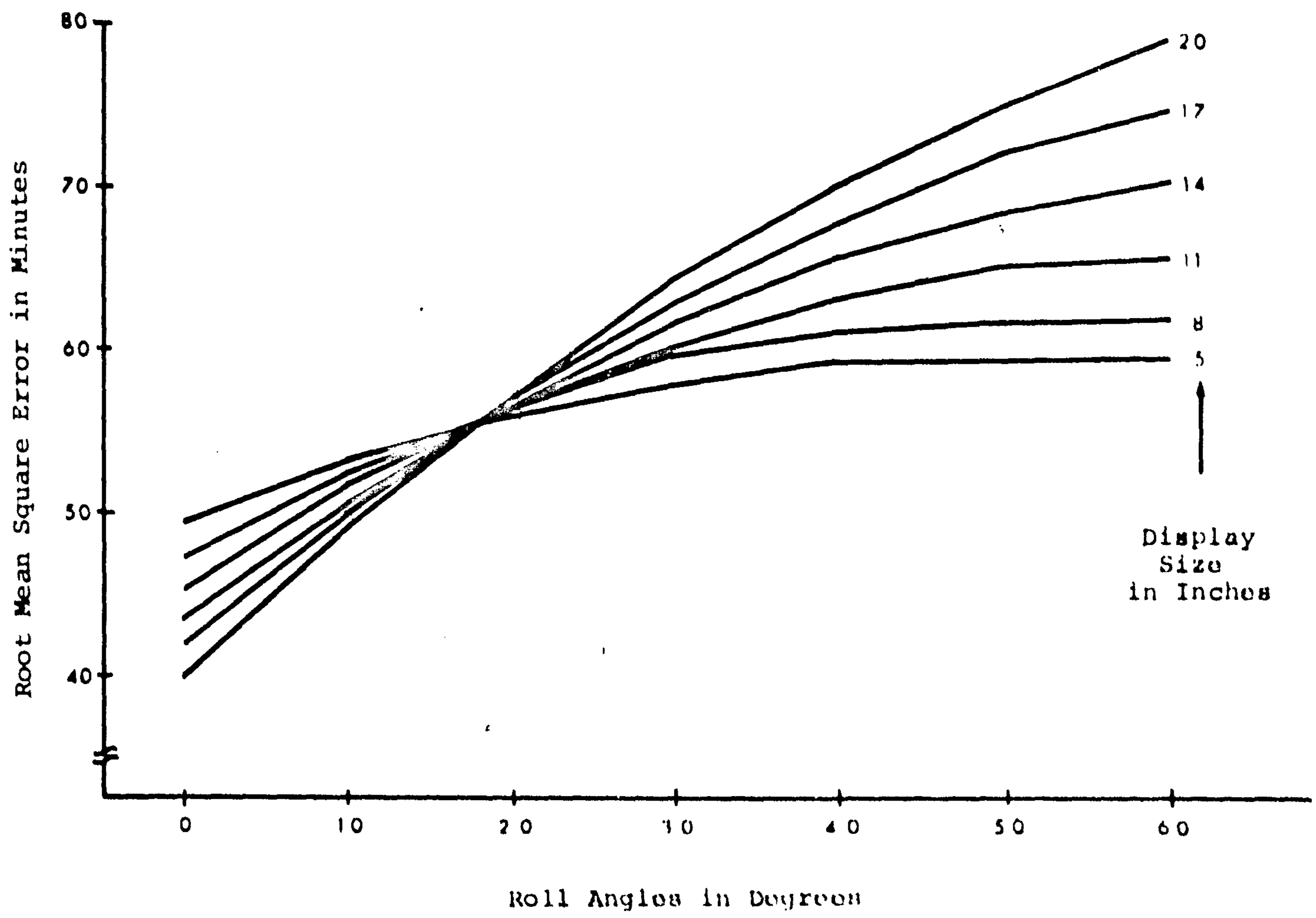


Figure 16. Accuracy of Roll Angle Maintenance as a Function of Display Size and Roll Angle. (Adapted from Ref. 97)

overall trends in the data, they conclude that an 11-inch display would appear to be the most effective tradeoff for minimizing errors over a wide range of roll angles.

In a separate experiment, Cross and Bittner determined the accuracy with which three naval aviators and three non-pilots could make absolute roll angle judgements as a function of display size. By verbal command, the experimenter requested that roll angles ranging from 60 degrees right roll through 60 degrees left roll be set in by the subjects using a joystick rate control. No roll angle scale was used. Correctness of response feedback was provided in order that learning could occur. Analysis of average errors and absolute average errors showed that display size did not affect the abilities of subjects to set in various roll angles. Further analysis of the data showed that an average subject should be able to set in a roll angle within $\pm$ 3.0 degrees on 99.97 percent of his attempts, regardless of the roll angle he may be attempting to establish. Figure 17 shows average absolute error (AAE) as a function of the roll angles which subjects were requested to establish using the VCAD. It is apparent from the figure that AAE was different as a function of the roll angle to be set in.

Cross and Bittner also investigated the effects of display size upon the ability of non-pilots to maintain pitch angles at plus or minus 75°, 45°, 30°, 15° or 0°. Five, 8, 14 and 17-inch display sizes were investigated. Sine wave forcing functions were introduced into both the pitch and roll channels, and the subjects' task was to operate a rate control joystick to maintain pitch attitude separately at each of the nine pitch attitude reference values. The tracking of pitch attitudes was performed for several variations in roll angle. Average absolute error and RMS error scores were computed as performance indices.

As Cross and Bittner point out, the amount of change in the position of the horizon line that results from an increment in pitch angle is a function not only of pitch angle, but also display size and viewing angle (i.e., sensor field of view). The relationship among these variables is shown in Figure 18. When display viewing angle is manipulated to maintain a 1:1 correspondence between the display and the real-world, the amount of change in the position of the horizon line that results from a given increment in pitch angle is the same, regardless of the size of display used. Conversely, if viewing angle is held constant while display size is varied, the amount of horizon line displacement per pitch increment increases as a direct function of display size. Consequently, larger displays provide a more sensitive index of change in pitch angle than smaller displays assuming that display viewing angle remains constant. Cross and Bittner held viewing angle constant while varying display size.

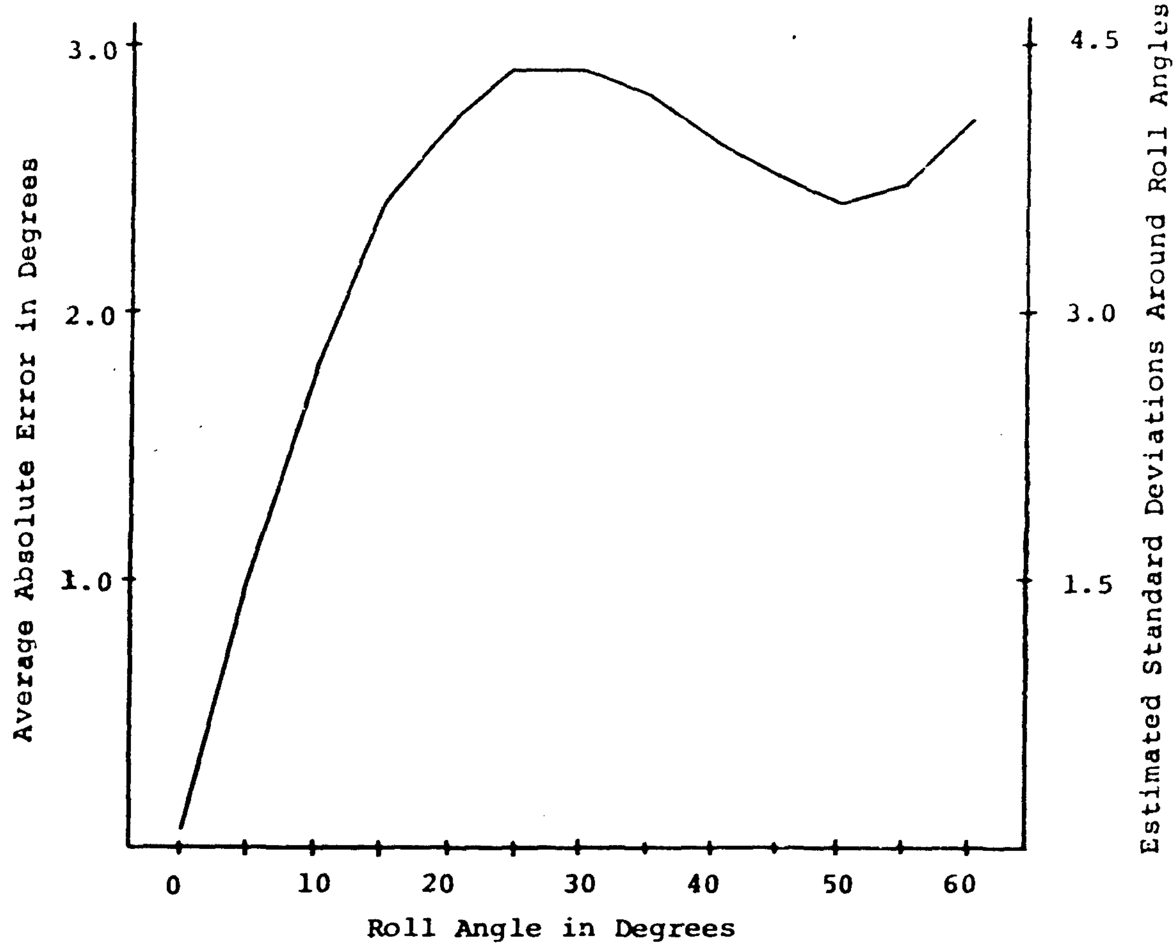
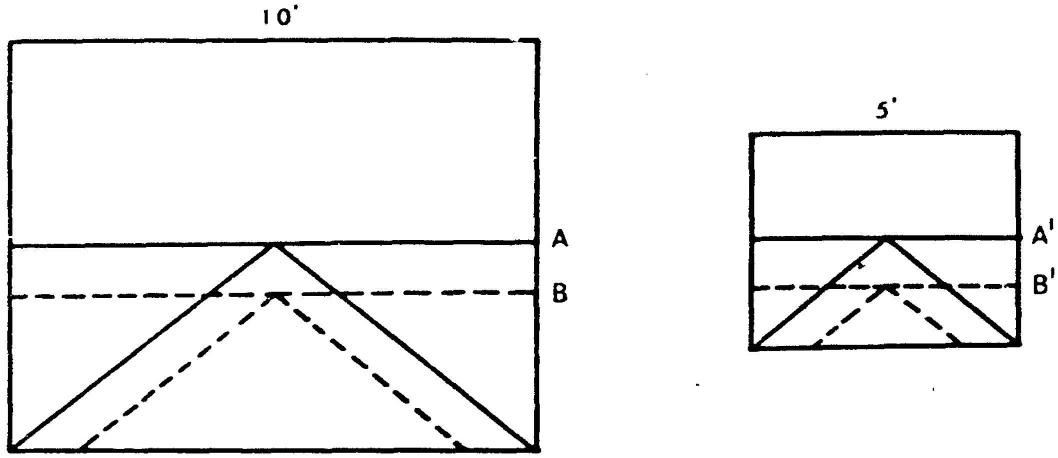
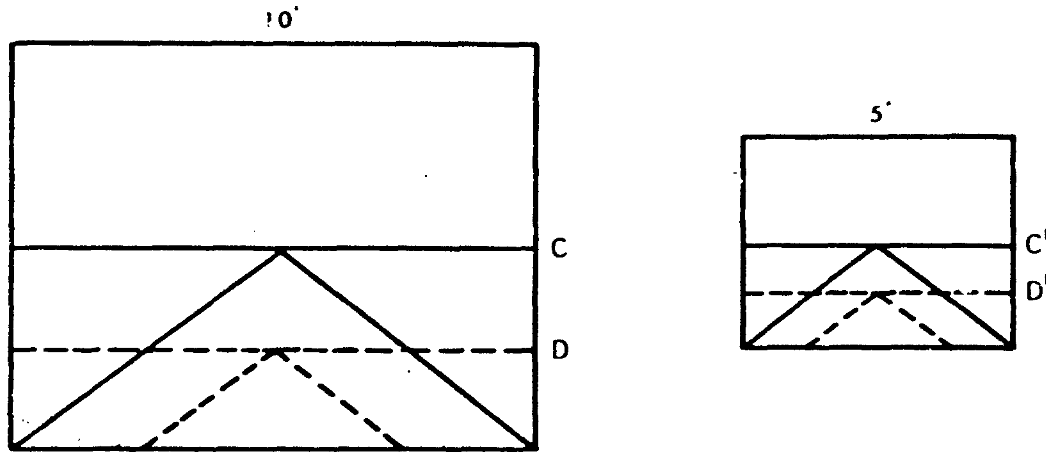


Figure 17. Average Absolute Error of Roll Angle Judgements as a Function of Roll Angle Magnitude. (Adapted from Ref. 97)



(a) 15° Pitch Increment When 1 to 1 Real World Correspondence is Maintained



(b) 15° Pitch Increment When 60°-Display Viewing Angle is Maintained.

Figure 18. Effect of Display Size and Display Viewing Angle on the Amount of Displacement of the Horizon Line Resulting from a 15° Increment in Pitch. (Adapted from Ref. 97)

As they point out, asking a subject to maintain a given pitch angle with varying sized displays is a legitimate procedure. However, once a subject is asked to ascribe numerical values to a given pitch angle (absolute judgement), the task becomes impossibly confusing. For example, if subjects were asked to judge the position of the horizon line according to a "real-world" criterion, error would automatically increase as a function of display size, at least for conditions wherein display viewing angle (sensor field of view) is held constant. Consequently, they did not require subjects to make absolute judgements of pitch angle as a function of display size in this study. Subjects only tracked pre-established pitch attitudes.

Results of the study are shown in Figures 19 and 20. Figure 19 shows the relationship between AEE (in volts) and display size. The data represent predictions for an average subject maintaining the zero degree pitch angle standard after training. Since there was no interaction between display size and pitch angle standard, the shape of the curve can be considered representative for all standards. It can be seen that AAE was found to be least for intermediate display sizes. The minimum point on the curve was found to correspond with a 12.25-inch display.

RMS error is shown in Figure 20 as a function of a display size and magnitude of the pitch angle standard. Because of the close proximity of the curves for the various display sizes, Cross and Bittner only published curves for worst and best case conditions. The curve for the five-inch display represents the worst case, while the computed curve for a 12.25-inch display represents a best case. Curves for all other display sizes fell within these bounds. The most striking effect in Figure 20 is the finding that the minus 75 degree pitch angle standard was clearly more difficult than the remaining standards. Otherwise, there was little difference among RMS error scores for the remaining standards. Of particular interest is the absolute magnitude of the RMS error data for the various standards. Considering the 12.25-inch display, RMS error was less than one degree for all standards except the 75 degree standard. Since RMS error is an estimate of the standard deviation of errors about the mean, it is quite apparent that the average subject could maintain pitch angle within three degrees of pitch angle standards from negative 45 degrees to positive 75 degrees over 99% of the time. The considerably degraded performance associated with the negative 75 degree standard was attributed to ineffective pitch angle cues available for this condition.

The following general conclusions appear warranted based upon the experiments of Cross and Bittner. The effects which display size had upon absolute judgements of pitch and roll angle magnitudes was quite small. Display size was consistently found to have an effect on the accuracy with which an assigned

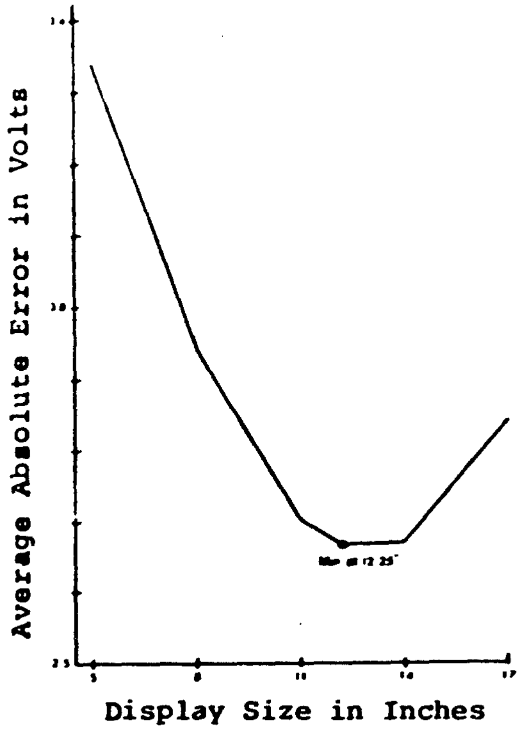


Figure 19. AAE as a Function of Display Size. (Adapted from Ref. 97)

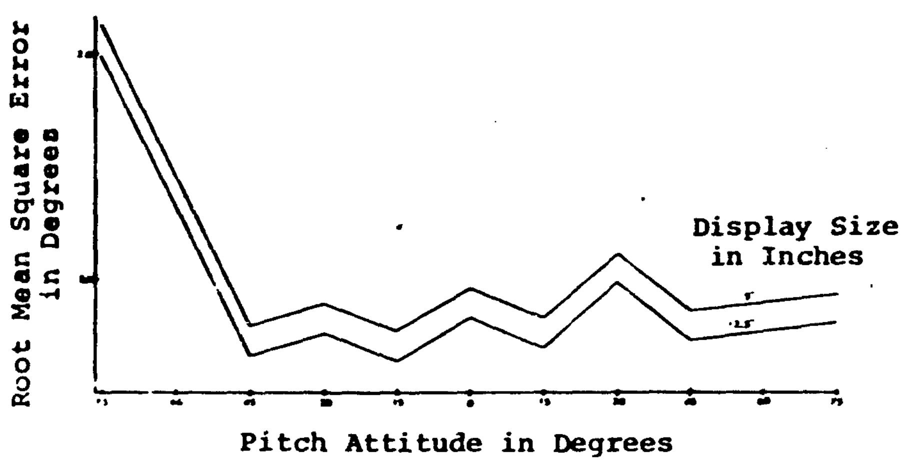


Figure 20. RMS Error as a Function of Display Size and Pitch Attitude Controlled. (Adapted from Ref. 97)

value of pitch or roll could be maintained. Intermediate display sizes resulted in the most accurate performance, although an "optimum" display size would have to be selected based upon the particular pitch or roll angle being controlled. Considering the pitch angle studies, performance was optimized for display sizes ranging from approximately 8 to 13 inches. The display size found best in these studies was the 11-inch display. In contrast, a rather pronounced interaction between display size and magnitude of the roll angle standard was found. Larger displays were favored if the standard was less than 18 degrees, while smaller displays were better for standards greater than 18 degrees. The display size which appeared to maximize judgement accuracy across all roll angles was an 11 inch display. When all results of these experiments are considered as a unit, the 11-inch display appears to represent an optimum trade-off.

The reader is cautioned against over generalization of these data, however. First of all, the data were collected using an eye-to-display viewing distance of 32 inches. Therefore, any generalization of the data to other viewing distances should be accomplished on the basis of visual angle dimensions rather than inches of display height or width. Second, the data were collected in the context of contact analog display system information content and presentation format. It would be expected that the effects of display size might be somewhat different for displays of lesser pictorial content and greater symbolic content. The use of pitch ladder scales and roll angle scales are two primary examples of how information content might influence the effects of display size upon absolute judgement performance if not continuous control performance. Similarly, performance might vary as a function of display viewing angle (sensor field of view). Also, in the simulation used, aerodynamic crosscoupling was not present. Additionally, many of the other flight tasks required of the pilot were not simulated. Finally, qualified pilots were not used in all of the experiments. It is unlikely, however, that this had any affect upon the data due to the relative simplicity of the tasks involved. For full task simulation, however, the use of qualified pilots would be a necessity.

CONCLUSIONS

Considering just electronic displays used for flight path control (EADI's), experimental data which have the most direct application are those published by Roscoe et al. (Ref. 284) and Cross and Bittner (Ref. 97). In these studies, terminal area flight control, approach and landing and a variety of other attitude control tasks were examined to determine the effects of display size upon task performance. There is some degree of correspondence between the results of the studies, even though

Roscoe, et al. used a projected periscope display while Cross and Bittner employed contact analog displays. Both studies concluded that displays with a diagonal dimension of approximately 11 inches resulted in optimal performance, with Cross and Bittner reaching this conclusion from investigations of pitch and roll angle control considerably in excess of those used by Roscoe et al. Additionally, Cross and Bittner also have shown that making pitch and roll angle judgements and continuous control of pitch and roll angles are not markedly influenced by display size when one considers that an EADI must be designed to produce acceptable control performance throughout a range of 360 degrees of both pitch and roll.

Based upon data obtained from projected periscope images of the real-world, Roscoe et al. have shown that a magnification of one (i.e., a display-to-real-world ratio of 1:1) is needed for acceptable approach and landing performance. The data of Cross and Bittner are predicated upon displays with a magnification of one. Whether this ratio will produce adequate pitch and roll scale factors for continuous control of all aircraft dynamics cannot be answered from their data. Indeed, the answer to this question cannot be provided without considering controller and system (aircraft) dynamic response characteristics in a closed-loop feedback system context. As discussed within the scale legibility portion of this report, relating display scale factor to continuous control performance is beyond the purview of this report. It must be pointed out that none of the reports reviewed within this section systematically varied electronic flight display scale factors for either pitch or roll attitude control. Thus, conclusions regarding display size which may be drawn from available data are limited to displays incorporating scale factors of 1:1.

Review of available data indicates that electronic flight displays ranging in diagonal dimension from eight through 17 inches produce similar control precision, with an 11-inch display providing for an acceptable tradeoff. These findings are based upon a viewing distance of 32 inches; display sizes would be linearally reduced for shortened viewing distances.

It would appear that additional research dealing specifically with display size for EADI displays is not necessary. What will be needed, however, are investigations of pitch and roll scale factors for particular aircraft applications.

SECTION IV

INFORMATION CODING

INTRODUCTION

Williams (Ref. 356) stated that flight is inherently a goal-directed activity and that every flight has a beginning and an end. In order to successfully complete this activity, a number of sub-goals must be established and achieved for all phases of the flight. These sub-goals necessary for flight consist of:

1. Direction of flight - ultimate goal.

2. The attitude of the flight - performance desired.

3. Mechanical operation of the craft to achieve the above.

It is hence necessary to provide the pilot with means of accomplishing these sub-goals. This requirement, an information system, must allow the pilot to set up indices of desired performance and to control the aircraft in order that the desired performance will be achieved. Additionally, the pilot must take into account other requirements of flight. These include the presence and flight path of other aircraft relative to his own, weather conditions, terrain features, flight regulations and the physical limitations of his aircraft. It is the express function of the on-board data management and display system to provide him with the above information.

Roscoe (Ref. 283) argues that the sub-goals of flight are related in a hierarchical fashion. Through direct manipulation of the controls, changes are introduced into the aircraft's attitude, thrust and external configuration, which in turn affects the craft's velocity vector and this indirectly affects the craft's position in space and time. These changes are in turn reflected by changes in the aircraft's display indices. Since information is conveyed by changes in these indices, it is necessary to decide upon a consistent and "natural" (Carel, Ref. 58) set of movement relationships in the display system. This is the basic problem in the design of integrated visual displays.

The concept of hierarchical relationship in the pilot's tasks provides the rationale for theological grouping of information into a relatively small number of integrated displays. This hierarchically related information should be presented in a common frame of reference or coordinate system. The difficulty occurs in trying to decide how far this integration will proceed. Analysis and experience suggest that at least two views of the

flight domain should be presented: a horizontal or downward-looking view for use in navigation and mission requirements and a vertical or forward-looking view used for flight control.

Simple combinations of a large number of information items in a single display unit does not necessarily result in an integrated display system. The underlying principle of display integration requires related information to be presented in a common reference system which shows the relationships among the items to be perceived. Additionally, it is necessary that this relationship be perceived directly by the observer. This necessitates keeping the display itself as simple and unencumbered as possible. On the other hand, it is necessary to include in the display sufficient information for the successful operation of the aircraft. These, and many other, restraints dictate symbolic coding of the information presented.

This section addresses the problem of how information is encoded in the display system, i.e., examine some of the symbol alphabets developed. But, in order to fully appreciate the strengths and weaknesses of the reviewed matter, we must ask ourselves what it is that one is looking for. By a definitive, but necessarily brief, statement of some of the problems and considerations in display coding, it is possible to ascertain where the present state-of-the-art in symbology research stands. This accomplished, an attempt is made to reduce the rather extensive amount of research done in the area of coding to manageable proportions and digest the results and recommendations found therein. By so doing it is possible to ascertain those areas where additional research is required.

Figure 21 indicates the general format for this section. Shape coding is examined first. This includes a review and summary of the general work in the area, followed by a closer look at some research aimed specifically at radar symbols. This is followed by a summary of findings and general recommendations. Next, the subject of color coding of information is addressed. Some of the major advantages and disadvantages of color coding are examined, pertinent research evaluated and recommended color alphabets summarized. Again, research recommendations are proposed. Finally, the use of flash rate as a coding dimension is addressed.

SHAPE CODING

Introduction

A shape code is used to symbolically or pictorially represent a given amount of information in a limited amount of space. Because of their capacity to transmit various amounts of information under a number of operating conditions, a large number of shape code alphabets have arisen in the literature.

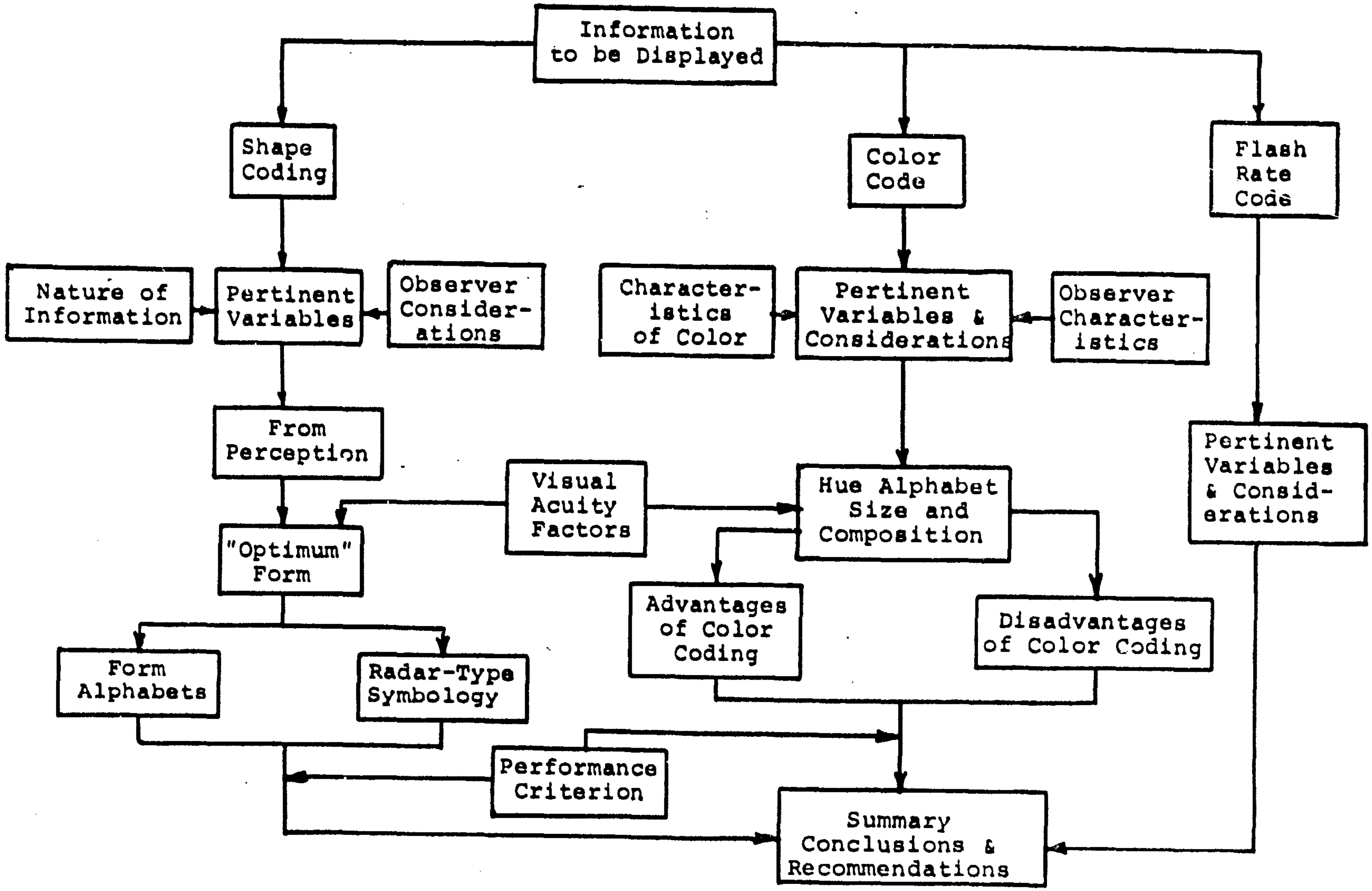


Figure 21. Information Coding Section.

It is impractical (or impossible) to consider all of them in this report. For this reason, this review has been limited to those studies whose results could make possible contributions to the establishment of optimal airborne electronic display symbology. Even with this restriction, it is necessary to limit this review to those studies conforming to a realistic design methodology. This is not to say that other studies not reviewed are not sound; rather their primary sources did not explicitly indicate the above criterion.

With the abundance of studies in the area of form perception and shape coding, it is necessary to ascertain what it is exactly that a given shape code is to do. Only after this has been established can the criteria for the selection of this code be spelled out. Without a selection criteria formerly fixed, journeys through the literature are frustrating and often unrewarding. With the selection criteria in mind, those studies which possess possible contributions to the development of an optimal shape code alphabet can be gleaned out. This, essentially, is what this review attempts to do. By specifying that the code (shape or other codes) is to be limited to electrically/optically generated airborne displays under operational conditions, and is to be used to transmit operational information through integrated displays to the pilot operating under operational stresses, selection criteria for the code can be established.

Criteria for the selection of shape codes (or any codes for that matter) should be established by answering at least the following questions:

1. What is the optimum shape (color, etc.) for the code to assume? In answering this question, all the parameters that are expected to interact with this symbol should be considered in the selection procedure. The amount of dynamic change present or expected, the criticality of the information, the presence or absence of other symbols, the effects of rapidly changing luminance levels must all be considered.

2. Number of categories - How many discrete symbols will be required to provide the necessary information in symbolic form? This minimum number of symbols should be considered with step number one since different shape alphabets have definite size limitations.

3. Minimum amount of information - What is the least amount of information that can be presented and still successfully perform the mission? If possible, a symbol type and alphabet should be selected in which a single meaning is assigned to each symbol.

4. Optimum symbol size - How large (bright, etc.) does the selected symbol have to be in order to provide good legibility under the range of operational conditions to be encountered? It is necessary to keep the symbol as small as practical in order not to interfere with the readout of other information, but large enough to ensure accurate transmission of the required information. This consideration includes the visual angle subtended by the symbol as well as the stroke-width-to-height of each symbol.

5. Spacing of symbols - What are the spacing requirements that need to be considered in order to present the maximum amount of information required on the display surface? The formatting of the symbology is important to produce the least amount of interference.

6. Absolute identification - Will it be necessary for the observer to read the symbol alphabet without reference to a standard? This consideration will limit the size and complexity of the alphabet selected.

7. Ease of learning - Is the alphabet selected such that it can be readily learned by the user population and not show a performance deterioration during adverse or emergency situations? The alphabet should be equally interpretable under adverse as well as normal conditions.

8. Safety factors - Is there a provision for a safety factor (an alphabet of less than the maximum amount of symbols) in the event it will have to be used in noise or less than ideal conditions? If the minimum amount of discriminability is left between symbols in an alphabet, the introduction of relatively low amounts of noise will, in most cases, significantly reduce performance.

9. Technical feasibility - Is the alphabet feasible for presentation with the equipment it is to be used with? The more detailed and complex the alphabet, the more sophisticated the generation equipment must be to present it with the desired resolution.

With the above usage restrictions and selection criterion, the literature produced little in the way of directly pertinent information. Most of the studies reviewed dealt with low-light levels under laboratory conditions. Almost all of the studies dealt with only one to two of the many parameters interacting with airborne display systems. In most cases, many of the significant variables were not even recognized (mentioned), let alone controlled for. Most of the subjects were operating in unknown or stress producing environments and consequently their results can be expected to vary from the performance of skilled subjects (pilots) familiar with the experimental conditions

(aircraft flight, etc.). For these and many other reasons, generalization from the literature to operational conditions is tenuous.

In light of the above discussion, why even bother reviewing many of the older studies on form perception and shape coding studies? There are several parts to the answer of this question. The first is that there have been "significant contributions" made by many of these older studies to the problem of information display systems. Even though those studies were unidimensional in nature, (one parameter varied and the rest of the world supposedly held constant), they tended to focus attention on several of the variables important to information coding (minimum size, viewing angle, form perception variables, etc.). Secondly, their lack of examination of the interaction effect of many of the variables impinging upon their results have spurred later researchers to challenge their results and in many cases to conduct better controlled experiments. Finally, even with the weaknesses and limitations of these findings, the results of many of these earlier studies have crept into the present-day thinking on display design. Valid or not, much of this thinking is passed on from one generation of displays to the next, with little consideration given to its applicability.

The following review of some of the more often quoted studies illustrate many of the above problems. The first few studies examined are concerned with establishing the "best" form or establishing those characteristics which go to make up the best form. With this goal in mind, consideration should be given to the parametric conditions (the many points along the continuum of performance) under which the particular form championed is to be viewed. In order to declare a particular form best, the conditions under which it is best must be specified. Systematic (factorial) testing and/or control of the many parameters which interact to influence observer performance should be conducted. Finally, care should be exercised in the development of the methodology in order to ensure that the resulting data will be a reliable measure of the parameters one wished to test.

The second group of studies looks briefly at the development of symbol alphabets. These studies are concerned with the development of groups of readily recognizable and easily discriminable symbols to be used on more complex displays.

Form Perception

Research on shape coding of information has its roots in early studies of form perception going all the way back to the work of H. C. Stevens in 1908 (Ref. 324), Geissler in 1926 (Ref. 129), Pease in 1927 (Ref. 262) and Kleitman and Blier in 1928 (Ref. 210). These early stirrings soon took on the form of

unofficial movements after the introduction of Gestalt Psychology (Kafka, 1935 - Ref. 187). As a consequence of Kafka's work with the Laws of Pragnanz, considerable research was generated in an attempt to ascertain the "best" figure in the Gestalt tradition. Fehrer in 1935 (Ref. 118) found that simple symmetrical shapes are most easily learned. Woodworth and Schlossberg in 1954, (Ref. 361) emphasized the virtue of symmetry. Fitts et al. (1956 - Ref. 122) found that figures symmetrical around the vertical axis led to somewhat better performance (accuracy of recognition) than those symmetrical about the horizontal axis. Attneave in 1957 (Ref. 11) found that observers rated simplicity of shape primarily on the number of turns in the contour and their symmetry and sharpness. Dardano and Donley (Ref. 99) found that complete figures (circles) were more discriminable than incomplete figures (1/2 circles). Gaito (Ref. 126) found the propensity to perceive a curved line as straight to be greater than the reverse.

In opposition to the Gestalt principles, Collier in 1931 (Ref. 83), Whitmer in 1933 (Ref. 353), King et al. in 1944 (Ref. 207), Casperson in 1950 (Ref. 60), Smith and Boyes in 1957 (Ref. 314) all demonstrated that triangles, rectangles, or crosses are superior or "better" than circles. Rappaport (Ref. 274) did not verify his hypothesis that symmetrical figures would result in better performance than an equally complex assymetrical figure. Deese (Ref. 104) found that when observers need only remember one form at a time, complex forms are more accurately identified.

Perhaps it would be of benefit at this point to ask just what this or that figure is "better" or "best" for. Certainly, if these early results are to be generalized to visual display problems, such important parameters as resolution, brightness contrast, ambient and background illumination, visual noise, exposure time, and redundancy cannot be dismissed. If we are to extend them to the complex visual displays addressed here, we must take into consideration such psychological, physiological, and social factors as individual motivation, psychological set, individual differences, response complexity, channel capacity, individual cultural orientation and form familiarity. Clearly the early studies do not control for these and many other variables, but they are considered here for their results have vectored later decisions on coding. Subsequent researchers have sometimes quoted these studies, somewhat out of context, to support their own findings, even though their studies were not comparable. Black on white, white on black, solid and linear, equal area and equal height forms have been stirred together without particular attention paid to design.

Several studies have produced results which indicate that the threshold of recognition of a visual test object is influenced to some extent by the shape of the object. Kleitman

and Blier (Ref. 210), for example conducted a study using solid black equal area forms on a white background to test subjects on direct and peripheral vision. Their findings indicated that the triangle was superior to the circle, square, or star for both direct and peripheral vision, and that the triangle has the lowest visual threshold of the forms tested. The difficulty with their results is that the equal area design gave the triangle the advantage in angular subtense. This variable was not discussed by the authors.

Collier (Ref. 83) presented seven different solid forms in a peripheral view study. His sizing method was not described. His scoring was in terms of extent of perimetric field and a subjective measure of certainty. He reports that equalateral and isosceles triangles are vastly superior, followed by the square, parrallelogram, circle, hexagon and octagon in that order (Table 3). Regardless of the sizing problem, it is obvious that confusion possibilities are greatest between the hexagon, octagon and the circle. Additionally, the two triangle forms used were not adequately described and consequently little weight can be placed on their reported advantages.

Munn and Geil (Ref. 251) also examined equal area forms viewed peripherally to determine what forms could be most accurately discriminated. Two forms were presented simultaneously in the peripheral area of vision, one stimulating the lateral portion of each eye. The subjects (four) were instructed to fixate on a central fixation point prior to exposure of the forms presented. Each form was 10 cm^2 and was cut out of black paper which was then placed in front of a light box illuminated by a 10 watt bulb. The forms were viewed from a distance of 60 cm. The box aperture was covered prior to exposure with white paper. The forms were presented in random order and orientations and at different peripheral angles (beginning at 85° and descreasing in 5° decrements). The subjects were not provided with knowledge of results.

Munn and Geil reported that the triangle was correctly recognized over the greatest parametric field followed by the square, circle, rectangle, and hexigon in that order. Again, angular subtense is possibly the explanation for the first three ranks. It is also obvious that only the triangle has no confusion form in the five symbol design.

Helson and Fehrer (Ref. 162) used six equal area solid black on white forms (area ranging from approximately 800-1,000 mm^2) in their study of light and form thresholds, just noticeable form and form certainty. The forms illumination levels were increased until accurate identification was obtained. The symbols were viewed from a distance of 275 cm (approximately nine feet). The results indicated that the triangle and the rectangle were the best forms (i.e. had the lowest light thresholds for just noticeable light). The circle did not place first on

Table 3. Summary of Results of Study by Collier. (Ref. 83)

FORMS	HORIZONTAL RIGHT		HORIZONTAL LEFT	
	Number of exposures	Per cent correct	Number of exposures	Per cent correct
Circle	77	69	50	68
Octagon	77	28	50	30
Hexagon	77	44	50	48
Square	77	74	50	70
Parallelogram	77	71	50	70
Equilateral Triangle	77	86	50	78
Isosceles Triangle	77	71	50	82
	539	63 av.	350	64 av.
	VERTICAL UPPER		VERTICAL LOWER	
Circle	38	38	50	50
Octagon	38	18	50	33
Hexagon	38	41	50	50
Square	38	74	50	76
Parallelogram	38	69	60	82
Equilateral Triangle	38	82	50	90
Isosceles Triangle	38	69	60	68
	266	55 av.	350	64 av.

any measure taken and was rated as "neither good nor bad". Table 4 presents a summary of the verbal reports given by the four subjects for the first 50 observations with each form. It is observed that the triangle was most correctly identified by the observers and showed the least amount of confusion with the other forms used. The advantage appears to be explainable in terms of angular subtense and/or confusion forms within the matrix.

Whitmer (Ref. 353) conducted a study in which he found that the rank order of different shapes, based on the percentage of correct discrimination, was triangle best, followed by diamond, square, rectangle, circle and hexagon.

King, Landis and Zubin (Ref. 207) using only triangles, squares and circles, found subliminal perception (using forced guesses) to exceed chance and that the triangle, though not significantly, did exceed the other two forms.

Hochberg, Gleitman and McBride (Ref. 168) believing that the previous conflicting reports were due to a lack of consideration of and control for the effects (background figure interaction) of area of the figure and specific framework effects, attacked the problem from a different direction in an attempt to gain better control over these variables. Instead of triangles, they used an equal area circle, square, and St. Andrews cross projected as bright forms (with increasing intensities) upon a dark screen. The circle required the lowest light level for recognition while the St. Andrews cross required the greatest illumination for visibility. In this case, visibility was inversely related to angular subtense in direct opposition to other equal area studies. They concluded that a "good" figure is compact, simple, symmetrical, and familiar, as expected in the Gestalt approach. They made no effort to explain their findings, which were contrary to prior findings, using white forms on a black background. Neither did they mention the possibility of a decrease in "perceived brightness" over large angular extents.

Hanes (Ref. 156) concluded that triangles, perhaps, have been most persistent in giving lower thresholds, but whether this fact still held above threshold was still open to question. He reasoned that if "compactness" was a factor in determining a threshold, it may also help in determining apparent brightness. In his experiment to test this latter point, he used circles, triangles, and squares each with three different areas: 0.003, 0.0123, and 0.17854 square inch. These figures when viewed at a distance of 24 inches, subtend visual angles of 9, 19, and 144 minutes of arc respectively. His five subjects varied the brightness of the variable shape to equal the brightness of the standard shape. The brightness levels were 0.1, 10, and 100 ml. Hanes found that with the triangle (with an area of 0.0031

Table 4. Summary of Results of Study by Helson and Fehrer, 1932

Reports from all Os on Form*

(First 50 Observations)

Figure Seen as	Figures Exposed: Tri.	Rect.	Sq.	Circ.	Semi-c.	Angle	Total	Av.	
Tri.	180	0	0	0	52	57	208	74.5	0.
Rect.			0	0		0	215	53.7	0.
Square	0	0	180	30	1	4	215	53.7	5.80
Circle	0	0	20	170	1	7	198	49.5	5.59
Semi-c.	4	2	0	0	124	12	142	35.5	7.0
Angle	6	0	0	0	6	120	132	33.0	8.51

*Numbers indicate number of times stimulus was identified as each of the reportable forms.

square inch and brightness of 0.1 ml) as the standard, the mean value of the equal sized square which appeared equally bright was 0.125 ml, but for the triangle the mean value was only 0.095 ml. (See Table 5). The triangle therefore, appeared brighter than the square. The column means in Table 5, however, indicate that while this relationship holds true in a majority of the cases, the shape which appears brightest is somewhat dependent upon size and brightness level used. When the two smaller sizes are used, the triangle has a consistently higher apparent brightness than do the other two forms, but for the larger sizes, the circle appears brightest. Hanes could find no single explanation adequate to account for these results.

These early studies have little to offer in the way of unanimous conclusions. They do, however, offer a possible rank order of the symbols examined with the top spot apparently going to the triangle (see Table 6), followed by the square, circle and rectangle respectively. Additionally, these findings indicated that apparent changes in visibility of the few symbols examined were a function of the presentation method, the interaction effect with similar figures and the luminance levels used.

Table 5. Summary of Results Comparing "Compactness" and Apparent Brightness.

Each entry is mean value in millilamberts for five observers which appeared equal in brightness to the indicated standard (after Hanes, Ref. 156).

	Standard									
Shape	Square			Triangle			Circle			
Area (sq. in.)	.0031	.0123	.7854	.0031	.0123	.7854	.0031	.0123	.7854	
Variable	0.1 mL. level									Mean
Square	.110	.106	.101	.121	.125	.117	.129	.099	.132	.116
Triangle	.099	.096	.101	.095	.100	.104	.105	.091	.124	.102
Circle	.104	.104	.093	.108	.123	.102	.091	.103	.105	.104
Mean	.104	.102	.098	.108	.116	.108	.108	.098	.120	
	10 mL. level									
Square	9.5	10.2	10.2	10.6	11.0	7.9	9.6	10.2	13.1	10.3
Triangle	9.2	9.2	10.1	9.5	9.8	9.1	9.2	8.7	12.8	9.7
Circle	9.3	9.8	6.8	12.4	10.1	7.0	9.9	10.3	9.2	9.4
Mean	9.3	9.7	9.0	10.8	10.3	8.0	9.2	9.7	11.7	
	100 mL. level									
Square	113	101	93	102	111	98	113	108	135	108
Triangle	114	91	94	124	88	101	94	81	115	100
Circle	87	95	66	115	102	63	105	101	94	92
Mean	105	96	84	114	100	87	104	97	115	

Table 6. Ranking of Forms for Studies Reviewed.

Author	Triangle	Square	Circle	Rectangle	Hexagon	Star	Other Cross	Parallelogram
Kleitman	1*	3	2			4		
Collier	1	2	4		5			3
Munn and Geil	1	2	3	4	5			
Helson et. al.	1	3	4	2				
Whitmer	1	3	5	4	6		2	
King et. al.	1	2	3					
Hockberg et. al.		2	1				3	
Hanes	1	2	3					
Fehrer		3	1		2			
Kafka			1					

* 1 = most discriminable; 2 = second most discriminable, etc.

Symbol Alphabets

The next group of studies reviewed used larger alphabets of symbols, but likewise failed to uncover those characteristics which go to make up the "best" figure.

When working with larger alphabets, it is necessary to select representative geometric forms from a large number of form families (star family, triangle family, etc.) in order to ensure a balanced design. Unbalanced designs (symbols selected from a small number of form families) of this nature will tend to be biased in favor of the forms selected.

Casperson (Ref. 60) conducted a study to determine the discriminability threshold of six different geometric forms and to relate their relative discriminability to three quantifiable aspects of their construction: (a) area of the figure, (b) maximum dimension, and (c) perimeter. To produce variations in the six basic forms, he constructed five different variations of each basic form (Figure 22). These figures, when equal in area, differed in maximum dimension and perimeter. Additionally, each set of figures was reproduced with seven different areas in order to measure discriminability thresholds. Six complete sets of stimuli were made for each of the seven areas. The figures were solid black photographic prints on semi-gloss paper, and the illumination on the cards was 11.2 foot-candles. The 20 male subjects viewed the stimulus cards from a distance of 20 feet with their chins in rests. They were instructed to report only the basic form name presented. Each subject had seven experimental sessions; in each session he judged a complete set of 30 figures (all with the same visual area) 24 times.

The results indicated a difference in discrimination in the six forms tested. The results tend to confirm earlier reports that circular and elloptical shapes are difficult to identify (Helson and Fehrer, Ref. 162). Area was found to be the best measure of discriminability for ellipses and triangles. Maximum dimensions predicted discriminability best for rectangles and diamonds, while perimeter was the best predictor for stars and crosses. As a group, the best predictor for all the forms was maximum dimension. In ranking the discriminability of the six basic forms, it was found that the triangles, rectangles, and crosses consistently maintained their position in the first three places, while the stars, diamonds and ellipses occupied the lower three places, regardless of the variable used to measure performance. A comparison of the variance contributed by the subjects with the variance due to form differences substantiates the hypothesis that forms do differ in their discriminability and that the differences among the individuals making the discrimination are small when compared with these form differences.

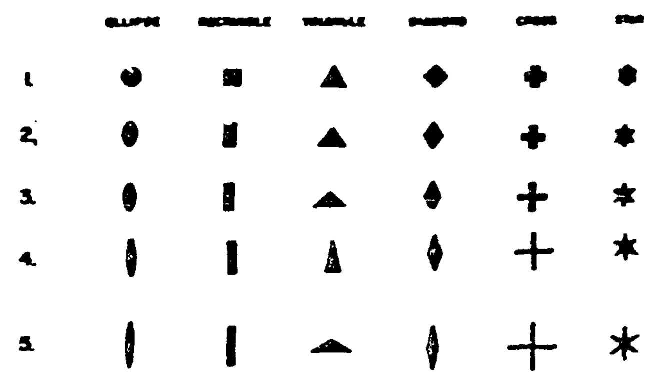


Figure 22. Forms and Variations Used by Casperson.(Ref. 60) The Seven Areas Used Were: .032, .072, .128, .200, .288, .512, and .800 cm^2.

Sleight (Ref. 310) attempted to obtain information on the relative discriminability of a number of geometric forms when the subject had to deal with a complex panorama before him. Six each of 21 different forms (Figure 23) were mounted on 1-1/4 inch clear lucite squares. The figures were the maximum size that could be inscribed in a 1-inch circle. A 25 inch circle painted flat white was used as the display background for the target symbol. Sixteen male and five female subjects sorted all six of designated target form into a compartment as quickly and as accurately as possible from a total of 126 forms.

The forms sorted most quickly were respectively: swastika, circle, crescent, airplane, cross and star (Table 7). When the subjects ranked the figures in order of "attention-getting value", the swastika ranked first followed by the cross, the star, airplane, crescent, diamond, circle, heart, and triangle in that order. There was a high positive correlation between the ranking of the figures according to sort time and the subject's ranking of items according to "attention-getting value".

Since the symbols used by Sleight were reasonably large, there was little possibility for blur to occur. In this type of study, there would appear to be an advantage given to the circle, even in the presence of several polygon forms, because of its size and area. Sleight also used an unequal sampling of form families with five polygon used as compared with only one triangle, square, and star. The numerous polygons and the circle accounted for a large percentage of the sorting error and must have contributed to the slow sorting time for the circle.

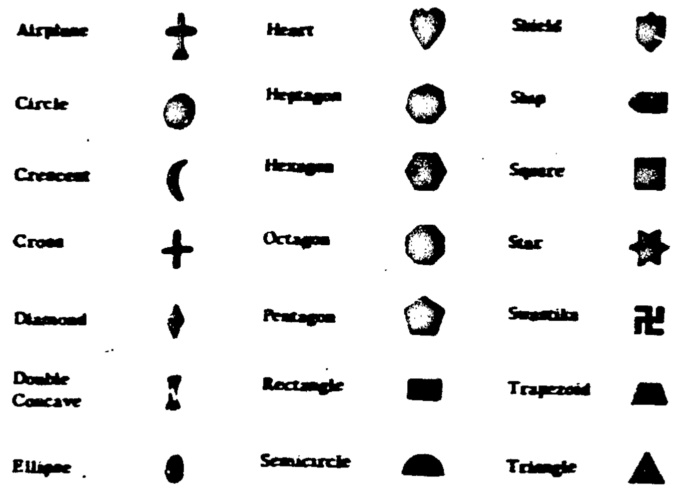


Figure 23. Forms Used by Sleight. (Ref. 310)

In a series of experiments, Bitterman et al. (Ref. 31) attempted to explore the implications of a diffusion model for visual form perception which was derived from the Kohler-Wallach theory of figural after effects (which states that corners tend to round-off, gaps close and fine detail to blur into larger detail). In his first experiment, foveal form threshold were measured in terms of the intensity of illumination required to identify luminous figures briefly exposed in a dark room (Figure 24). Significant variance due to form was found in the thresholds for these simple figures of equal area. Inspection of the graph in Figure 25 reveals a rather marked linear relationship between the two variables (luminance required for detection and parameter to area).

In the Bitterman study results, the square was frequently called a circle at pre-threshold levels, and the triangle was also mistaken for a circle (but not as often as the square). The cross was frequently called a diamond, the X a square, the I a triangle with the apex down, the L a semicircle or a half-moon, and the H on occasion was called a butterfly. The circle was rarely called anything but a circle. In general, as the diffusion model suggests, corners tend to round and gaps tend to close.

Table 7. (a) Mean Sorting Time and (b) Relative Discriminability of the Six Forms. (from Sleight, Ref. 310)

Table (a)

Mean Times for Sorting Six of Each Form and Groupings by Significance of the Difference Between Mean Times

Group	Form	Mean Time* (.01 min.)	SD	Skew-ness***
A**	Swastika	11.4	1.74	-.689
	Circle	15.2	4.75	.568
	Crescent	18.5	10.63	.761
	Airplane	27.9	13.24	.111
	Cross	29.1	16.74	.663
	Star	30.4	12.75	.972
B	Ellipse	40.0	26.80	1.220
	Rectangle	45.3	27.90	.806
	Diamond	47.2	22.29	1.238
	Triangle	53.7	28.22	.765
	Square	58.0	34.00	.679
C	Heart	66.0	52.72	.699
	Ship	70.2	34.35	1.150
	Semicircle	71.5	42.77	.793
	Pentagon	73.4	36.34	.495
	Trapezoid	77.3	46.65	1.086
	Shield	83.5	54.62	1.488
D	Octagon	94.7	54.88	1.088
	Double-concave	99.3	71.06	.895
	Heptagon	103.2	53.38	.972
	Hexagon	107.7	53.79	.731

* Each mean presented here is based on the last two trials for all Ss combined (N = 42).

** Groups denote forms, each of which is significantly different from all other forms (at the 1% level) except those within the same bracket. For example, the swastika is significantly better than the ellipse, the ellipse is significantly better than the heart, and so on.

*** Skewness is calculated using the formula three times the mean minus the median divided by the standard deviation. In a perfectly symmetrical distribution the obtained value would be zero.

Table 7. (a) Mean Sorting Time and (b) Relative Discriminability of the Six Forms. (from Sleight, Ref. 310)

Table (b)

Relative Discriminability of Geometric Forms as Determined by (a) Mean Selection Order, and (b) Mean Sorting Time*

Form	Rank by Selection Order	Rank by Sorting Time
Swastika	1	1
Cross	2	5
Star	3	6
Airplane	4	4
Crescent	5	3
Diamond	6	9
Circle	7	2
Heart	8	12
Triangle	9	10
Double-concave	10	19
Semicircle	11	14
Shield	12	17
Rectangle	13	8
Ellipse	14	7
Ship	15	13
Square	16	11
Trapezoid	17	16
Pentagon	18	15
Hexagon	19	21
Octagon	20	18
Heptagon	21	20

* Rank order correlation = .79

Form	Area (Square inches)	Perimeter (Inches)	Perimeter/Area
Circle	.25	1.77	7.08
Square; diamond a/	.25	2.00	8.00
Square; diamond a/	1.00	4.00	4.00
Triangle	.25	2.27	9.08
L	.25	2.31	9.25
Cross; X a/	.25	2.69	10.75
Cross; X a/	1.00	5.36	5.36
T	.25	2.69	10.75
H	.25	3.02	12.10

a/ Identical forms differing in orientation by 45°.

Figure 24. Description of Figures Used in First Study by Bitterman et al. (Ref. 31)

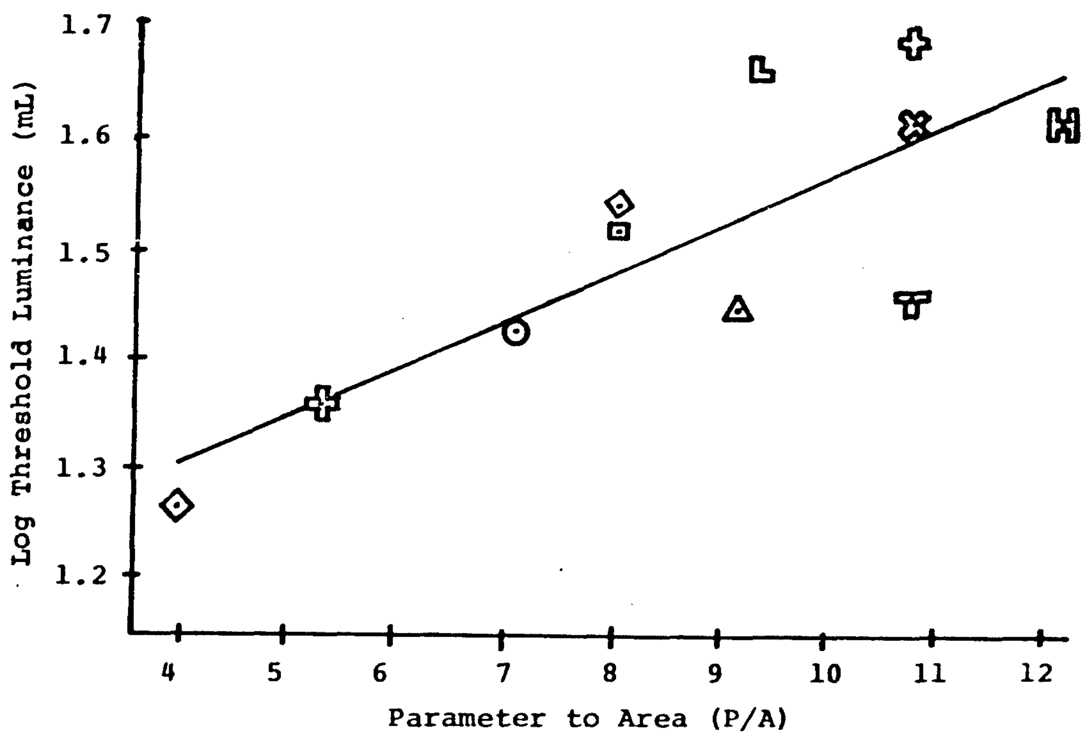


Figure 25. Required Luminance Threshold as a Function of Parameter/Area. Note that the Two Lowest P/A Values Represent the 1.00 $inch^2$ figures and the Remaining Figures are for the Smaller 0.25 $inch^2$ figures. (After Bitterman et al., Ref. 31)

In the next series of parametric experiments (Bitterman, Ref. 31), form thresholds were found to vary inversely with exposure-time, with area, and with magnitude of critical detail. Qualitative as well as quantitative reciprocity of time and intensity was discovered; distortion of form (blurring of fine detail) appeared with short exposure times which were comparable to those obtained with low illumination levels.

The fifth experiment in the series was designed to examine the role of critical detail in form perception. In the figures used (Figure 26), length and/or area increased progressively while perimeter/area (P/A) decreased slightly.

Examination of the results presented in Figure 27 suggests that the principle source of variation for the crosses, X's, and L's was magnitude of the critical detail measured in terms of the lengths of the arms constituting the interior angles. Thresholds for crosses and X's decreased in a similar manner with increasing length of details despite the fact that for the crosses, P/A incresses markedly and area remains the same while, for the X's, P/A decreases markedly and area increases significantly. From these results, Bitterman concludes that the perception of form, at low levels of illumination, is limited primarily by local diffusion (diffusion of the detail) which obscures critical detail, rather than by the relative amount of diffusion from the figure as a whole (expressed in terms of P/A).

From the data collected in his experiments, Bitterman made the following general conclusions:

1. Brightness thresholds vary inversely with exposure time and with area, but appear unaffected with rather extensive changes in configuration.

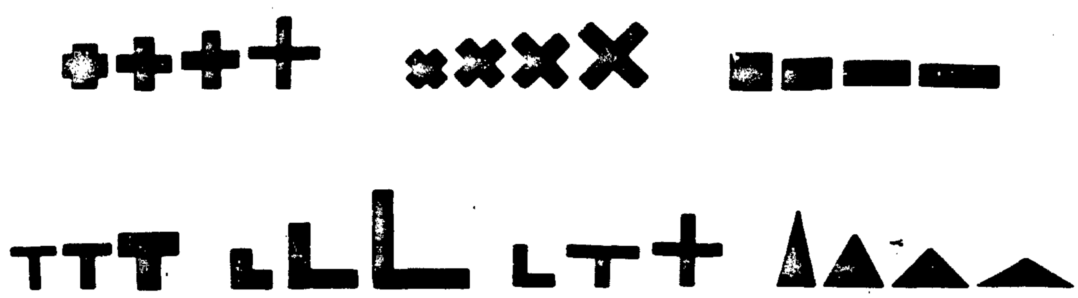


Figure 26. Forms Used in Experiment V.
(Adapted from Bitterman et al. Ref. 31)

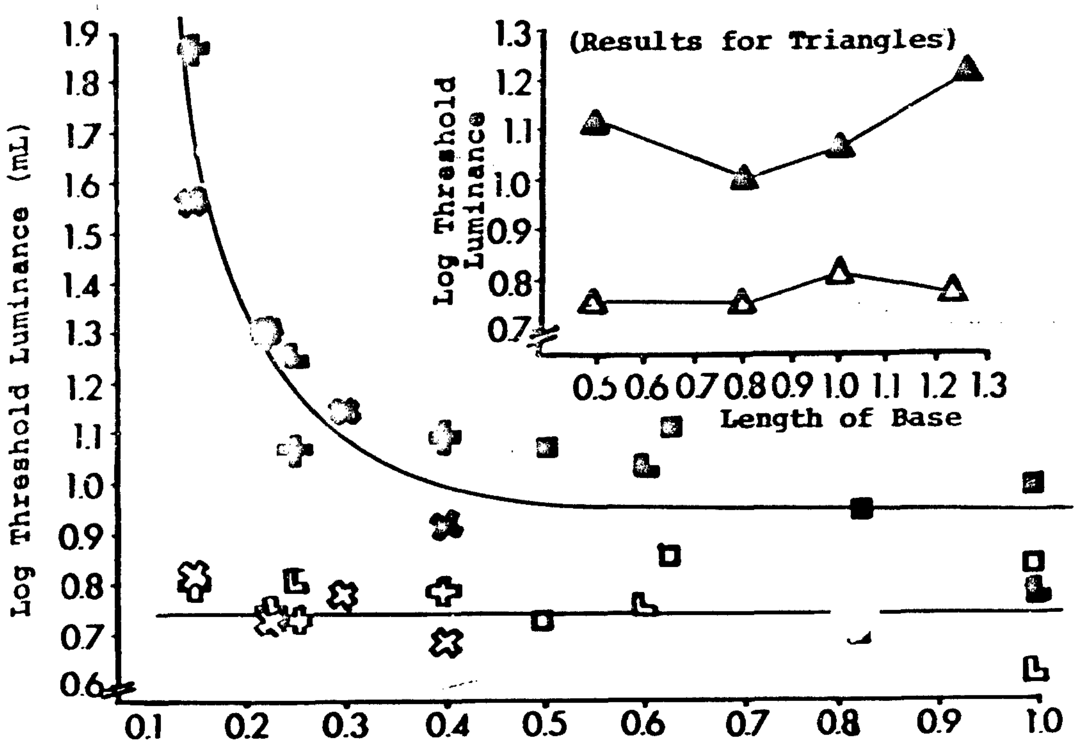


Figure 27. Brightness and Form Threshold as a Function of the Length of Critical Detail. (After Bitterman, Ref. 31)

2. Form thresholds vary inversely with exposure time (increase exposure time decreases threshold), with area (increased area decreases threshold), and with magnitude of critical detail (increased size of detail decreases symbol threshold).

Bowen et al. (Ref. 38) surveyed the literature and were unable to find any definitive rules for establishing easily recognizable symbols. Rather, they found distinctive combinations of features for each shape: no one of which was absolutely necessary. They, therefore, attempted to establish the rank discriminability of a set of 20 geometric symbols under various conditions of degradation of noise, distortion, and blur and to select subsets of these symbols that would yield minimum confusion. The shapes were selected so that each would appear distinctively different, simple, have few elements, but in some sense be symmetrical (Figure 28). Slides were made for each symbol under each of the 12 viewing conditions and were back-projected onto the center of a five by five inch opal glass screen producing symbols of 0.5 inch height and stroke-width-to-height ratio of 1:10. Viewing distance was 50 inches and the

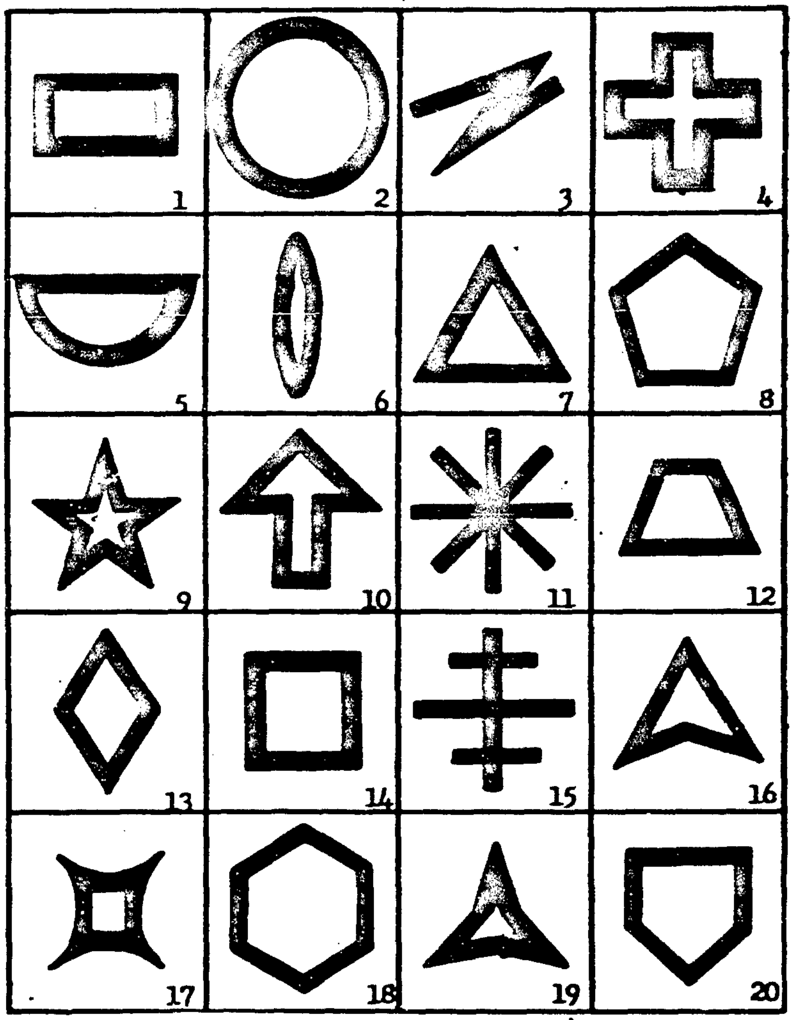


Figure 28. The 20 Symbols Selected by Bowen et al. (Ref. 38)

brightness of the display was 4 to 5 foot-Lamberts (dependent on the noise condition of the slide). Seven subjects were each shown the 480 presentations individually for 0.5 seconds.

The results indicated no significant difference in the performance among the Subjects. (Table 8, however, indicates a significantly different score in the accuracy of recognition for each symbol). Increasing the amount of noise and the amount of distortion significantly lowered performance, but increasing the amount of blur (within the range used in this study) did not. Bowen hypothesized that blur causes a lack of definition to the small elements and therefore renders the background more uniform,

Table 8. Percentage of Correct Recognition. (From Bowen et al., Ref. 38)

Symbol No.	Percentage Correct	Symbol No.	Percentage Correct
1	.916	11	.785
2	.898	12	.756
3	.869	13	.779
4	.869	14	.506
5	.839	15	.762
6	.881	16	.553
7	.875	17	.458
8	.833	18	.720
9	.839	19	.559
10	.863	20	.690

while affecting the solid dominant parts of the figure to only a small extent. Hence, the overall loss of resolution is counterbalanced by an increase in the effective figure-ground contrast.

The interaction term (which is defined as the degree of variation in a score which is attributable to the combination effects of two or more of the conditions and which is distinct from the effects due to the conditions considered individually) "Noise by Distortion by Blur" was significant and is graphed in Figure 29. As these three conditions combine into progressively more and more adverse display conditions, performance deteriorates at an increasing rate. While blur alone did not affect the scores significantly, it does enter into this interaction term. Hence, Bowen concluded that some blur is tolerable, provided that the other display conditions are fairly good. However, when the other conditions are poor, the presence of blur will recruit to the other factors to degrade symbol recognition.

The results of the experiment were entered into a master confusion matrix which describes the probability of any of the 20 symbols being responded to when one symbol was displayed. From this matrix, optimum subsets of symbols were found and are presented in Table 9.

Table 9. Optimum Sets of Symbols.
(Adapted from Bowen et al., Ref. 38)

Number of Symbols in Set	Recommended Symbols*	Articulation scores for conditions: Best	Average	Worst
2**	1 & 2; or 1 & 3; or 2 & 3; or 7 & 14; or 5 & 7; or 5 & 14.	1.0	1.0	1.0
3	1, 2 & 3; or 5, 7, & 14.	1.0	1.0	1.0
4	1, 2, 3, & 4; or 5, 6, 7 & 14.	1.0	.99	.99
5	1, 2, 3, 4, & 5; or 4, 5, 6, 7 & 14.	1.0	.98	.91
6	1, 2, 3, 4, 5, & 6.	1.0	.98	.91
7	1, 2, 3, 4, 5, 6, & 7.	1.0	.98	.83
8	1, 2, 3, 4, 5, 6, 7, & 8.	1.0	.97	.79
9	1, 2, 3, 4, 5, 6, 7, 8 & 9.	1.0	.95	.69
10.	1, 2, 3, 4, 5, 6, 7, 8, 9, & 10.	1.0	.94	.67

* For additional symbols use: 11 but not with 3
12 but not with 5 or 7; and
13 but not with 8.

** Symbol numbers refer to symbols shown in Figure 28.

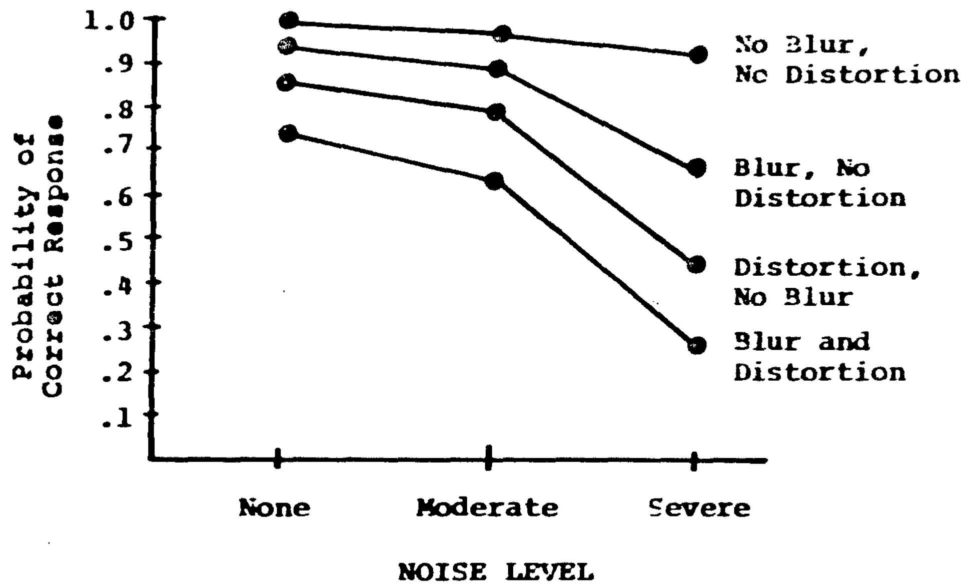


Figure 29. The Interaction Effect of Noise, Distortion, and Blur Upon the Probability of Correct Response. (After Bowen et al., Ref. 38)

While the above combinations are optimal, any combination of the first ten figures should yield good results, however, a square and a rectangle should not be used together. In general, symbols 15 thru 20 should not be used, if possible. The number of symbols should be kept minimal, and under adverse conditions, no more than six symbols should be used.

A second experiment was designed to provide information about optimum size and stroke-width-to-height ratio for symbols to be used for tasks similar to those found in operational radar centers. The stimuli were: (a) a circle, (b) a variation of a cross, (c) a square, and (d) a triangle. Each symbol used had three sizes (0.25, 0.375, and 0.50 inch) and three stroke-width-to-height ratios (1:6, 1:8 and 1:10). The subject's task was to count the number of occurrences of a specific symbol as quickly and as accurately as possible when they were displayed.

The results indicated that the cross was counted most rapidly in all three size categories. The triangle turned in the poorest performance with regard to counting speed. The 0.5-inch symbols were counted the fastest with stroke-width-to-height making no difference for this size. For smaller size symbols, however, the thinner stroke-width-to-heights were superior.

Based on the above data, Bowen et al. made the following general recommendations:

1. Symbols should subtend a minimum of 20' of arc, but if the viewing distance is longer than the normal 28 inches it should form a visual angle of about 22' of arc.

2. The stroke-width-to-height ratio should be 1:8 or 1:10 for symbols of 0.4-inch or larger viewed up to a distance of seven feet.

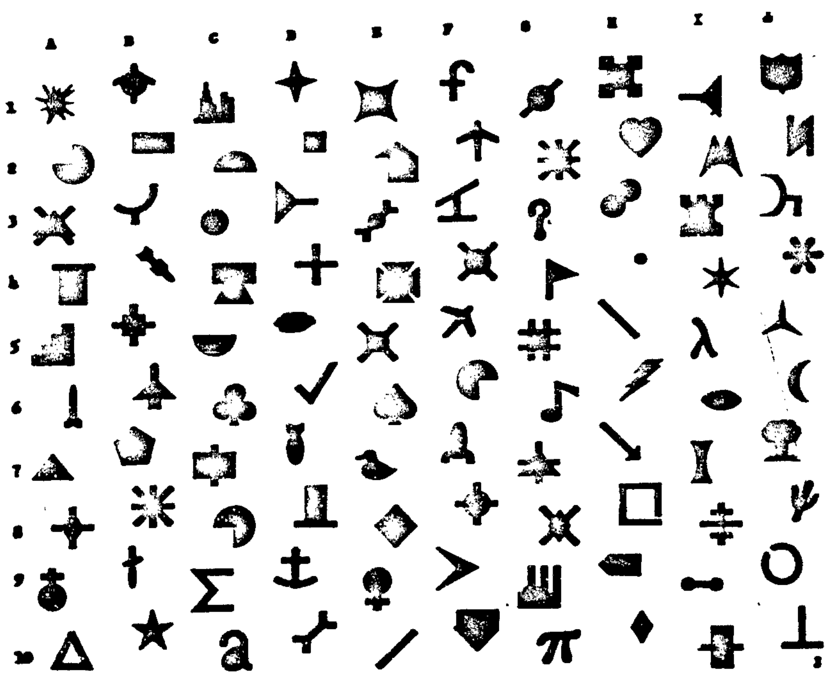
3. The best presentation rate was found to be about one symbol per 0.7 second.

The results of Bowen's study and his recommendations have appeared in many handbooks, guides and later studies on coding. Valid or not, his efforts appear to be the first attempt to establish guidelines for symbol construction. Unfortunately, there appears to be no follow-up work attempting to validate his recommendations.

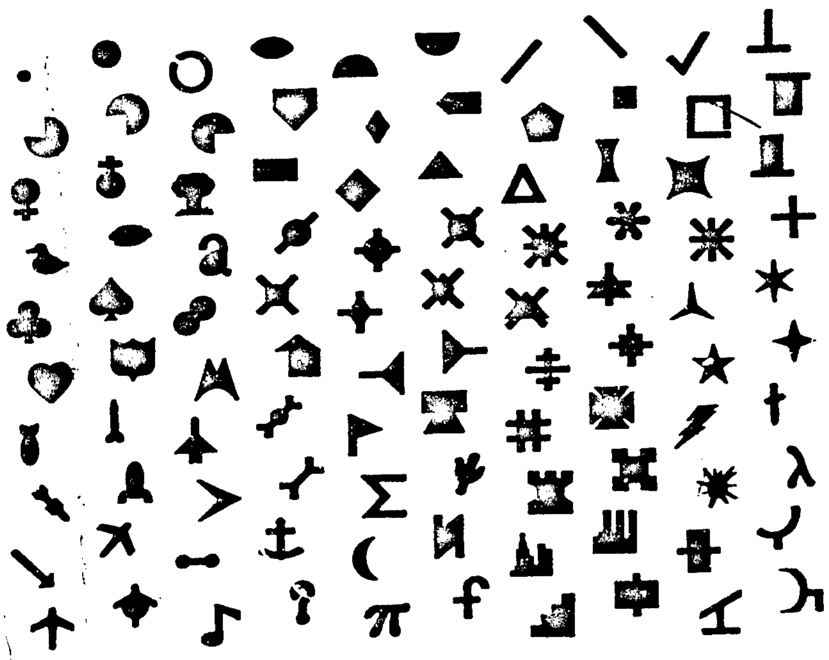
Since the symbols used in this study were presented in various orientations, the question of the context in which the symbol is presented becomes apparent. Additionally, the orientation of the symbol relative to the observer is perhaps a factor in the discriminability of certain figures (Form Number 11 proved less efficient in experiment number one where it was presented in isolation than it did in experiment Number II where it was presented in connection with other symbols).

Williams and Falzon (Ref. 357) investigated some of the variables thought to effect symbol discrimination and search time on complex Air Force information systems. One hundred symbols were derived and presented in five staggered ten by ten matrices and five ordered ten by ten matrices. Each symbol was projected for 0.5 second and viewed by six subjects viewing them from 45% left, 0^o, and 45^o right of center (20 feet from the screen). The symbol brightness was 20 Ft. Lamberts, and the background brightness was 2 Ft. Lamberts. The symbols subtended a visual angle of 20 minutes of arc (see Figure 30).

The results indicated that the type of matrix was not significant for search time or for accuracy. Viewing angle was significant for accuracy, but not for search time. At the center viewing position, area type forms (Table 10) were recognized most accurately, but at the right and left positions, perimeter type forms were recognized overall with most accuracy, followed by the pictorial type forms and then by the combined geometric forms.



a. Sample of the Random Matrix



b. Sample of the Ordered Matrix

Figure 30. Symbols Used by Williams and Falzon. (Ref. 357) Figure 30-a is Representative of the Random Matrix, Figure 30-b of the Ordered Matrix.

Table 10. Assignment of Figures to Experimental Categories, (After Williams and Falzon, Ref. 357)

Assignment of Symbols to Experimental Categories

Simple X Perim.	Simple X Area	Comb. X Perim.	Comb. X Area	Pict. X Perim.	Pict. X Area
A-10	A-5	A-8	A-3	A-6	A-1
B-10	A-7	B-5	A-9	B-3	A-4
D-1	B-2	B-8	C-4	B-4	B-1
D-4	B-7	D-6	C-7	B-9	B-6
E-10	C-2	D-10	D-3	D-7	C-1
F-9	C-3	E-3	E-2	D-9	C-6
H-4	C-8	E-5	E-9	F-2	D-5
H-5	D-2	F-4	G-5	F-5	D-8
H-8	E-1	F-8	G-7	G-3	E-6
H-10	E-4	G-1	H-1	G-4	E-7
I-4	E-8	G-2	H-3	G-6	F-7
I-7	F-6	G-8	I-1	G-9	H-2
J-4	F-10	I-8	I-2	H-6	I-3
J-5	H-9	I-9	I-10	J-3	J-1
J-9	I-6	J-10	J-2	J-6	J-7

Williams and Falzon make the following recommendations for the selection of symbols to be used in displays with a large number of symbols present:

1. Simple geometric symbols are recommended if high accuracy and low search time are required and the center viewing can be used.

2. If the right and left viewing angle must be used (but angles not greater than 45^{o} from the center), then simple geometric and/or pictorial-perimeter type forms are recommended (the latter being the best).

3. Combined geometric forms, as used in this experiment, were not recommended.

Results found in the above experiment indicated that solid geometric-type symbols were not recognized with sufficient accuracy for use in complex Air Force displays. In order to obtain a list of combinable symbols for use in system displays, Williams and Falzon (Ref. 358) conducted a similar experiment with the twenty-five symbols shown in Figure 31.

Six individuals familiar with the system viewed the 25 symbols under conditions stated for the study. During each trial, the symbol was projected on the screen from 0.5 second subtending a visual angle of 10 minutes of arc.

Combinations using outlined diamonds proved rather poor and were often confused with other symbols in the matrix (Table 11). Outlined squares and circles, on the other hand, seemed to yield satisfactory combinations. Outlined triangles were superior to outlined diamonds, but were still rather poor when compared with the square and circle combinations for accuracy. Search time rankings indicated that square and circle combinations could be located quicker than triangle or diamond combinations. Straight ahead again proved best for search time, followed by right and left positions of the display.

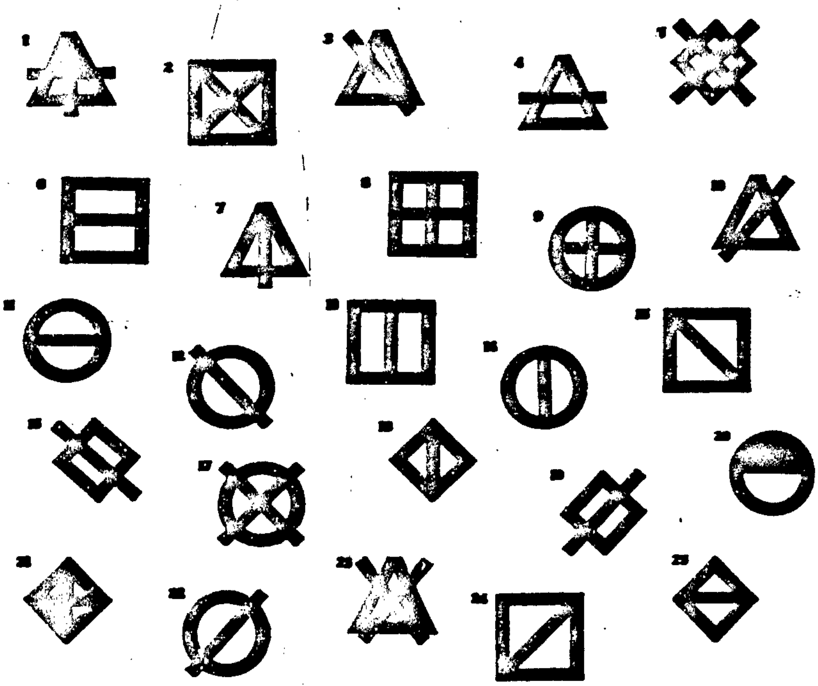


Figure 31. Figures Used by Williams and Falzon. (Ref. 358)

Table 11. Search Time Rank Order of Symbols. (After Williams and Falzon, Ref. 358)

Search Time (Sec.)	Frequency Per Measure	Cumulative Frequency - All Measures	Symbols From Figure
3.98	1	1	12
4.00	1	2	22
4.17	1	3	13
4.23	1	4	20
4.40	1	5	8
4.83	2	7	6, 24
4.90	1	8	11
5.33	1	9	3
5.50	1	10	9
5.70	1	11	2
5.90	1	12	10
6.17	1	13	7
6.23	1	14	23
6.33	1	15	15
6.46	1	16	14
6.60	2	18	1, 5
6.87	1	19	18
7.13	1	20	4
7.33	1	21	25
7.36	1	22	19
7.73	1	23	17
8.33	1	24	21
8.43	1	25	16

The circle-X (Symbol #17, Figure 31) was often confused with the square-X (Symbol #2). If the circle-X was not viewed at the center position, the extended diagonals seemed to cause the figure to appear as a square-X.

Summary

With the exception of the study by Bowen, et al., none of the above studies presented the symbols being discriminated in a realistic operational situation. Hence, the validity of generalizing these findings to radar or other electronic display situations appears to be limited. Likewise, the limited scope of the responses required of the subjects in these studies could hardly be compared to the complex response requirements of the operational situation. Later studies will show a definite interaction effect between these two important parameters. Also, the somewhat arbitrary manner in which the symbols were selected for testing, the limited number of types of symbols and the restricted nature of the testing done on the symbols selected does not appear to be conducive to broad generalizations of the recommendations derived therefrom. Be this as it may, the recommendations by the above authors have been broadly generalized and appear in many recently published studies.

Nonetheless, the above studies are not without merit. When applied to situations comparable to the tested situations, the general recommendations made appear to be quite valid. Unfortunately, the recommendations forwarded are not unanimous in nature. The guides proposed by Bowen et al. are diametrically opposed to those proposed by Williams and Falzon (i.e., Bowen suggests that modifiers - slashes or wings added to a basic figure - should not cross, distort or interfere with the primary symbol, while Williams and Falzon contend that modifiers contained within the primary figure lead to fewer confusion errors than extended modifiers). Based on the sparse evidence provided by the other studies reviewed and on the general recommendations from the area of form perception, it would appear that the recommendations made by Bowen et al. would be more valid for use on electronically generated display. This is not to say, however, that these symbols (presented on Figure 28) are universally applicable to all display situations. Careful consideration of the display, the environment in which it is to operate and the tasks demanded of the observer must be taken into consideration when generalizing this (or any) symbology to a new display situation.

Radar-Type Symoology

In the early days of radar, a very limited number of symbols could be generated on radar scopes. This limited alphabet quickly became a usable, if not standardized, target vocabulary. As technology advanced, however, newer equipment permitted the generation of complicated new symbols which soon displaced some of the older symbols. Unfortunately, this change did not constitute an orderly growth from the original alphabet. New meanings were assigned to older forms and new forms replaced older symbology. Recent state-of-the-art advances enable the

radar screen to present the observer with much more information much more rapidly. Computer generated synthetic video has transformed the traditional CRT into a meaningful picture of action with targets completely identified as clear symbols on an uncluttered background. Map overlays, terrain features, equipment position, check procedures, and much more can be presented upon demand.

With this capability, there is a temptation to build large vocabularies of meanings based on information which the computer can provide. Consequently, the appearance of newer, more sophisticated equipment will generally mean the introduction of a newer set of symbology to go with the equipment. Yet, as far back as 1949 (Ref. 127), Gebhard warned that these complicated codes are of little value unless they can be interpreted by the operator under field conditions. Several studies have been made in an attempt to ascertain the "best" set of symbology (Honigfeld, Ref. 171; Davis, Ref. 101), but again they have failed to come to any unanimous conclusions or specific recommendations. Bergum and Burrell (Ref. 28) recommended a standardization of radar symbology before the problem intensified. Honigfeld (Ref. 171) reviewed the literature in an attempt to formulate guidelines for standardization of radar symbology, but was unable to specify a standard alphabet. With this obvious need for standardization and limitizing, it is difficult to understand why new codes continue to appear.

The literature indicates that each new code designer leans heavily on earlier studies which appear to support his own particular theory. Many of these studies have been repeatedly summated without reference to the original conditions of the studies, and consequently many of the original weaknesses in coding have been perpetuated. It is obvious that these often quoted studies have influenced current thinking concerned with radar symbology, but with the multitude of new variables associated with newer equipment it is difficult to see how much of the earlier work can be directly applicable. A careful evaluation of the situation is certainly warranted.

As stated above, little of the preceding data can be applied directly to radar symbology. However, some of the general recommendations found in the above literature could possibly be of value. These include:

1. The suggestion of an interaction effect when highly similar symbols are utilized in a limited coding system. Symbols from the same or similar geometric family (i.e. triangles) tend to appear more similar as viewing conditions are degraded.

2. Consideration should be given to the apparent changes in visibility of an individual symbol with different types of presentation methods. The same symbol will not necessarily be

equally discriminable in different display formats (i.e., in presence of clutter, noise, etc. as opposed to a uniform display background).

3. The characteristics contributing to the legibility of symbols, usually a function of the form family from which the symbol was derived, should be maximized.

4. The number of symbols presented and the amount of information that must be encoded in each symbol should be weighted against the amount of information the operator needs and can efficiently handle.

True radar simulation studies are limited in number and in scope. The studies that have been concerned with radar simulation have tended to point out equipment problems rather than dealing with problems associated with symbology. The fact is that radar symbology has a number of unique parameters, many of which have not been examined at all. In addition to the considerations listed on page 53 dealing with general coding (which apply equally well here), the following variables must be considered:

1. Types of Presentation - What effects does the compression or expansion of information have on man's ability to comprehend slowly or rapidly changing situations?

2. Kinds of Information - How can computers be best used to decrease the complexity of the information presented and increase man's capacity for decision making?

3. Search Area - How are detection time and accuracy affected by increasing or decreasing search area?

4. Target Discrimination - What variables should be controlled for in order to increase discrimination of targets? Target discrimination on a CRT screen appears to be a function of: Relative motion of the target, brightness of the target and of the screen, type of symbol used, viewing distance, ambient and background illumination, size of the symbol, display size, and many more.

5. Irrelevant Information - To what degree does the presence of irrelevant information degrade operator performance?

6. Information Processing - How much of the information presented on a radar scope can the operator process under normal and stress producing operational conditions?

7. Spatial Characteristics - How similar should the display be to the real-world situation?

8. Psychological Stress - What effect does the increased speed, and complexity of the tasks associated with radar operations have on human performance? In addition, consideration should be given to the physical environment and possible perceived detrimental outcomes (i.e., the perception of danger).

With the above considerations in mind, we will proceed to the literature.

Attneave (Ref. 11) reports a series of experiments which appear to have some important implications as to how one perceives spatial relationships among abstract visual stimuli. He notes that complex visual objects are not only harder to reproduce from memory than simpler ones (Attneave, 1955), but also harder to learn by name and to match. In the study reviewed, he attempted to determine quantitatively definable aspects of figure "complexity", the relationship of judged complexity to information content of the figure, "degrees of freedom", compactness and several other variables. Seventy-two randomly shaped stimuli (Figure 32) were constructed using differing numbers of turns, degrees of curvedness and symmetry. These shapes were projected (for a period of 10 seconds) upon a wall screen in the front of the room in which the observers were seated for a period of 10 seconds. One hundred and sixty-eight airmen basic trainees served as subjects and rated the figures as "Extremely Simple", "Very Simple", "Simple", "Medium", "Complex", or "Very Complex". The size of the viewed symbol and viewing distance was not specified, but obviously varied with seated position.

The results of this study indicated that whether the shapes were angular, curved, or mixed made no significant difference in judged complexity. Symmetrical shapes, however, were judged more complex than assymetrical shapes with the same number of independent turns. Symmetrical shapes were judged less complex than assymetrical shapes with the same total number of turns. Consequently, the number of turns in the shape was the most

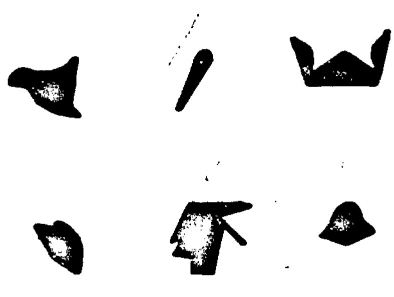
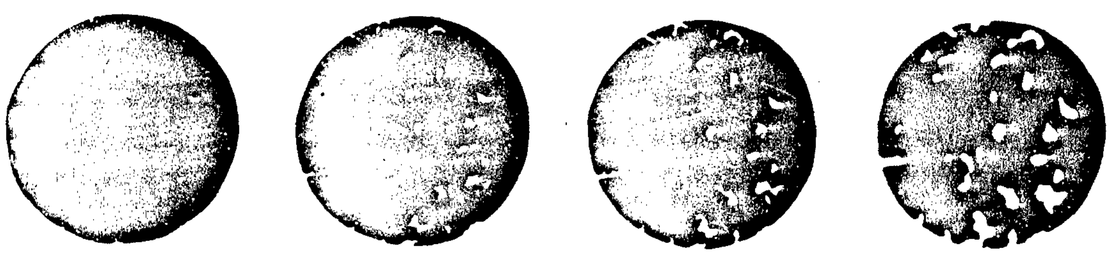


Figure 32. Representative Figures Used in Study by Attneave.(Ref. 11)

important determinent of judged complexity. The results also indicated that the curved shapes, although they appear no more complex than angular shapes, contain more information per symbol. Attneave concludes that this is valid since curved shapes require more dimensions for their specification than angular shapes.

The implications of Attneave's findings are (a) symmetrical patterns or shapes may appear to possess more meaning (contain more information) and be more easily interpreted than assymmetrical patterns or shapes with the same number of turns and (b) the difficulty of pattern recognition increases as a function of the number of turns in the symbol.

Baker, Morris, and Steedman (Ref. 13) created nonsense forms by random filling of a 300 x 300 cell square matrix to investigate factors of radar target recognition in air-to-ground systems. The forms created varied greatly in visual subtense, area and the number of changes in the direction of the peripheral outline (See Figures 33 and 34). The resolution was varied from .00 (perfect resolution), .01, .02, to .04-inch blur-disc diameter and the area of the display ranged from 6, 12, 16, to 24 square inches. Four different orientations of the displays were also used to reduce the effects of learning. Subjects were under a monetary incentive plan to maintain motivation. Subjects were seated individually in front of display (distance not specified). Each subject's task was to locate on a problem display a specific target shown to them on a briefing display. The results indicated that the time and error scores increased as a function of: (a) an increase in the number of irrelevant forms on the display, and (b) an increase between the resolution of the reference photograph of the target and the target as it appeared on the problem display. They found the absolute resolution of the forms to be of little value so long as the resolutions of the referenced form and the problem form were the same. Improvement shown with practice appeared to be a result of the subject's



.00 .01 .02 .04

Figure 33. General Appearance of the Matrix Forms at the Four Different Blur-Disc Diameters Measured in Inches. (After Baker, Morris, and Steedman, Ref. 13)

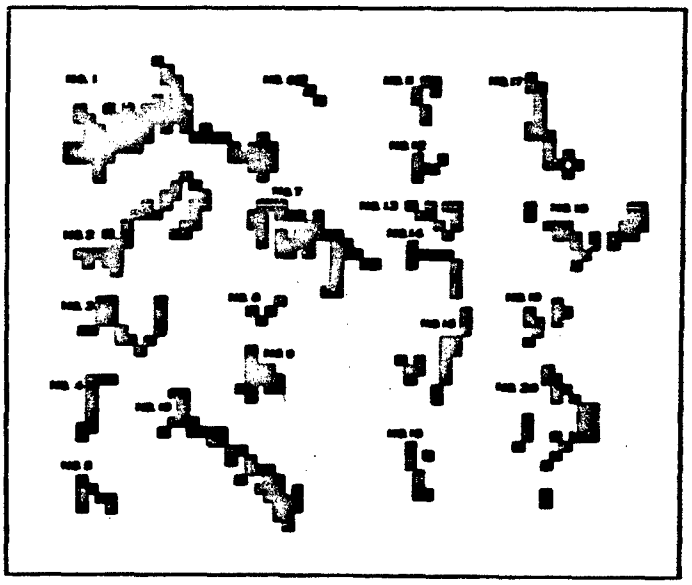
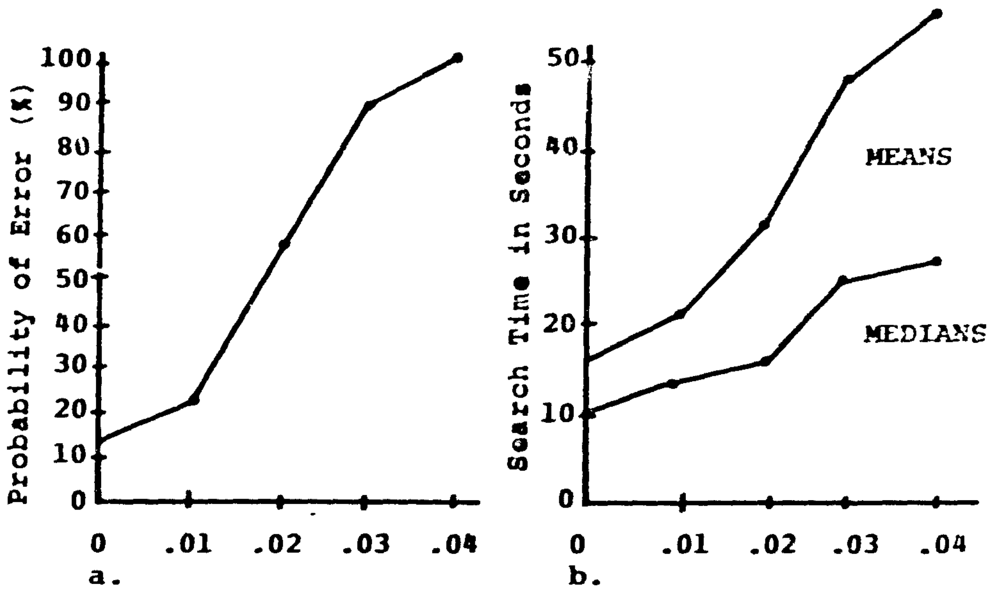


Figure 34. The Twenty Targets Used in the Experiment. Target Size Ranges from Three Cells (No.6) to 78 Cells (No. 1). Note that Five of the Targets are Discontinuous, i.e., they Consist of a Cluster of Cells, not all of which are Connected. (From Baker, Morris, and Steedman, Ref. 13)

ability to learn what effect a change in resolution will have upon the appearance of the target form rather than an increase with the general familiarity with specific targets and search areas. The performance data also indicates that the location of the target on the display affects performance. It was found that as the ratio of the target area to the area of the smallest circle which would enclose the target increased, search time and errors increased. Finally, increasing the blur disc diameter decreased the subject's performance (Figure 35).

Steedman and Baker (Ref. 321) made a follow-up investigation of speed and accuracy of target recognition as a function of the displayed size and resolution of targets. Circular problem displays were cut from the basic 12-inch square 90,000 cell matrix giving circular discs of 7.8-inches diameter. The five problem discs were then photographically reduced so as to result in a series of displays with diameters of 1.95, 3.90, and 5.85 inches, and matrix cell sizes of .01, .02, .03, and .04-inch respectively. Resolution of the matrix cells for the



Differences in Blur-Disc Diameter (in inches)
Between Target and Search Area Forms.

Figure 35. Probability of Error (a) and Search Time (b) as a Function of the Amount of Blur Present. (After Baker et al., Ref. 13)

largest cells were .00 (perfect resolution), .02, .04, .08 blur disc diameter. Four groups of 16 subjects were used, each group taking one fourth of the total of 16 treatment conditions. The 24 targets selected at random (ranging in size from three cells to 78 cells) were viewed at four different orientations (90°, 180°, 270°, and 00°) at a distance of 24 inches. (See Figure 36). The subject was presented with a "briefing target and then required to locate the same target in the presented "problem display". A monetary incentive was used to maintain a high level of motivation in the subjects.

The significant finding was that both criterion measures, search time and errors, remained relatively invariant until the visual angle subtense of the maximum dimension of the targets fell below 12 min. arc (See Figures 37 and 38). Hence, assuming a 12-inch viewing distance, a target must have a minimum size of 0.042 inch as displayed in order to expect relatively accurate and rapid recognition under ideal conditions. Where practical, minimum visual angle of target detail should be about 20 seconds of arc to insure recognition.

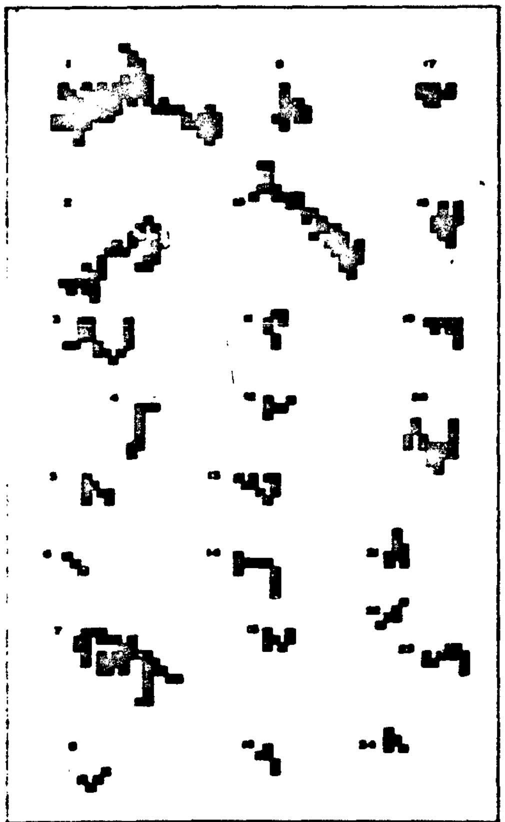


Figure 36. The 24 Targets Used in the Study Ranging in Size from 3 Cells (Number 6) to 78 Cells (Number 1). (After Steedman and Baker, Ref. 321)

In this experiment, the subjects always "knew" the target would be "there" and thus allowed a probability of error in that in the practical radar situation, the operator is not certain that there is a target "out there".

Gerathewohl, et al. (Ref. 134) conducted an experiment to study the effect of noise on relative form discrimination. Twenty-four subjects viewed four targets (circle, square, triangle and cross) each with an area of about 70 mm^2. (The square was approximately 8.3 mm on each side at a simulated distance of 10 miles). The targets were randomly arranged on 4 target circles, each of which included three of the above figures, on a PPI scope with a surface lumination (at 20 revolutions per minute sweep rate) varying from 4.0 to 10.5 ml

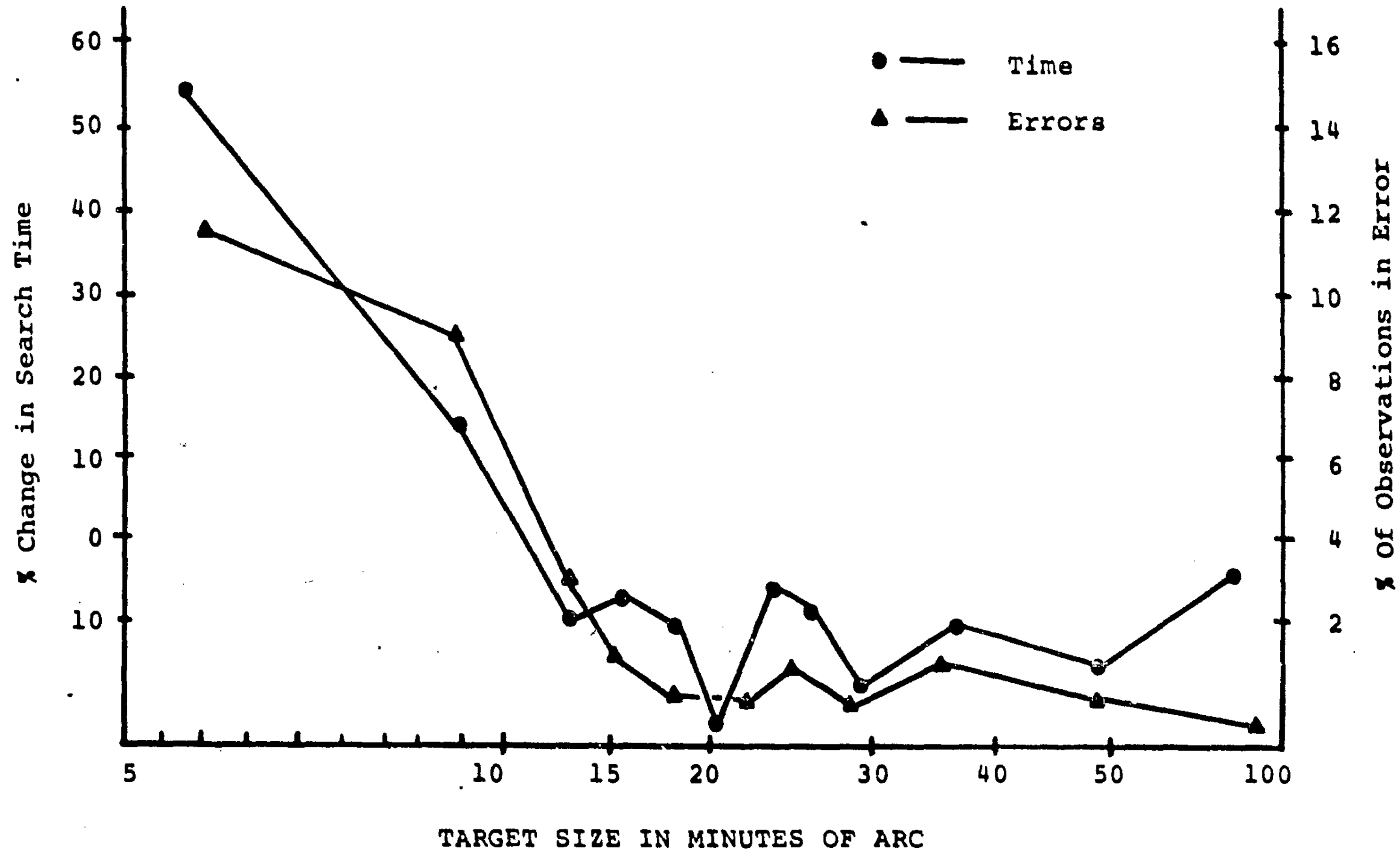


Figure 37. Search Time and Frequency of Error as a Function of Visual Angle Subtended by Target. (After data from Steedman and Baker, Ref. 321)

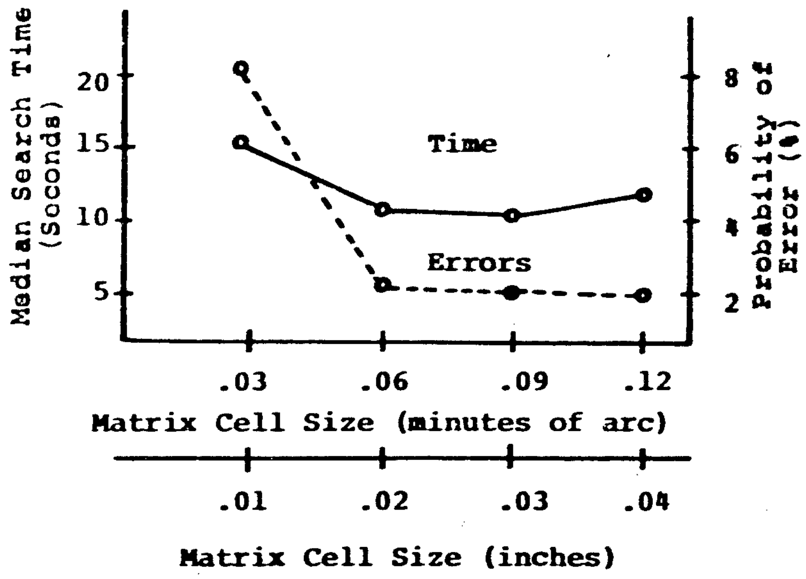


Figure 38. Search Time and Probability of Error as a Function of Matrix Cell Size. Each Point Represents 1538 Observations. (After Steedman and Baker, Ref. 321)

and with target lumination ranging from 60.0 to 375.0 ml yielding a continuously changing target to background contrast of from 18:1 to 36:1. The subjects viewed the targets one at a time at a simulated range of 10, 20, and 50 miles (Figure 39).

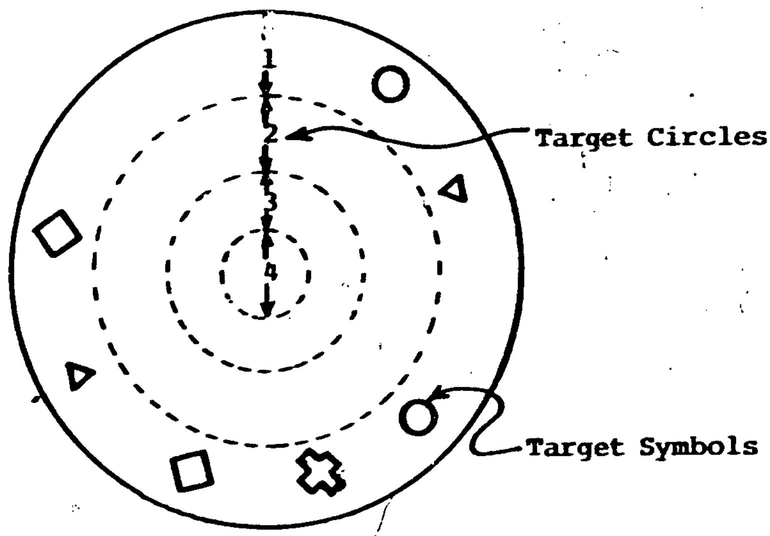


Figure 39. Schematic View of Target Symbols and Target Circles Used by Gerathewohl et al. (Ref. 134)

The relative discriminability of the four forms are shown in Table 12. The triangle ranked the highest, followed by the square, circle and cross in that order. Out of the 864 identifications per symbol, the triangle was misidentified 379 times; the square, 556 times; the circle, 625 times; and the cross, 671 times. The proportion of error for the cross was 0.77. There was a tendency for all the figures to be called a triangle. These data correlate reasonably well with findings of studies on form perception discussed earlier in this section.

The relative discrimination of all the targets was smaller at the 50 mile range than at the other ranges. However, there were more targets identified correctly at the 20 mile range than at the 10 mile range. The orientation of the target may have had a slight effect on accuracy of discrimination, but this effect was small when compared with the figure characteristics. (See Table 13.)

Dardano and Donley (Ref. 99) investigated the discriminability of five geometric figures which were selected for convenient generation from sine-waves and for ease of encoding with additional information. Independent variables in their study were: (1) density level of the presentations (24 and 48 symbols), (2) ratio of each target symbol (1 circle : 1 cross, 1 circle : 2 crosses, and 1 circle : 5 crosses), and the number of symbols to be discriminated (4, 8, 12, 16 and 24). Twenty subjects viewed 30 slides on a simulated planned position indicator radar scope.

Each subject sat directly in front of the screen and his viewing distance was self-determined (and unspecified). Symbols used are presented in Figure 40.

Results of this study indicate that the cross-within-circle and the cross were most discriminable. Dardano and Donley suggested that the straight lines were a characteristic of the most discriminable symbol. The circle and the half-circle were

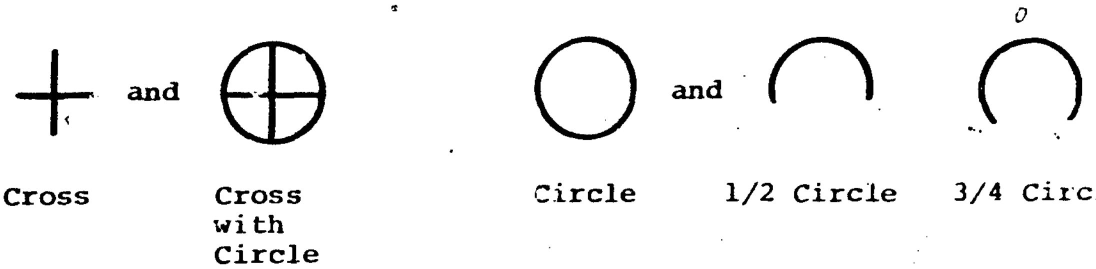


Figure 40. Symbols Used by Dardano and Donley. (Ref. 99)

Table 12. Relative Discriminability of the Four Targets. (After Gerathewohl, Ref. 134)

Rank	Target	Correct Responses						Totals	
		10 miles		20 miles		50 miles		Correct Responses	Percent
1	Triangle	168	58.3%	184	63.9%	133	46.2%	485	56.1
2	Square	104	36.1%	111	38.5%	93	32.3%	308	35.6
3	Circle	76	26.4%	87	30.2%	76	26.4%	239	27.7
4	Cross	78	27.1%	80	27.8%	35	12.2%	193	22.3
		426	Total Correct Responses	462	Total Correct Responses	337	Total Correct Responses	1,225	

Table 13a

Frequency and Percent of Reports for Each of the Four Targets Regardless of Accuracy and Range

	Triangle	Square	Circle	Cross	Total
Frequency	1,303	919	650	581	3,453*
Percent	37.7	26.6	18.8	16.9	100

*No response was given in three cases.

Table 13b

Frequency of Misidentification of the Three Differently Oriented Targets in all Four Target Circles

	Triangle	Square	Cross
Range of Errors	112-134	123-198	210-238

Table 13c

Frequency of the Responses with Respect to the Four Target Circles

Target Circles

1		2		3		4	
Correct Responses	Errors	Correct Responses	Errors	Correct Responses	Errors	Correct Responses	Errors
294	570	306	558	314	550	311	553
34.0%		35.4%		36.3%		36.0%	

Table 13. Frequency of Reports (a), of Misidentification (b), and Responses (c) for the Experimental Targets. (After Gerathewohl, Ref. 134)

less discriminable, and the three-quarter-circle was least discriminable (accounting for 31 of the total of 39 errors of confusion). The cross-within-circle was confused with the circle (three times out of four) as the outer contour of the circle appeared to be dominant over its interior lines.

The study of these symbols, excluding the three-quarter-circle, was repeated under field conditions by Dardano and Stephens (Ref. 100) to determine (a) any change in the discrimination order reported earlier, (b) effect of size on discrimination, (c) optimal size for presentation of the symbol, and (d) effect of unique characteristics of electron generation of symbols on their relative discriminability. Again the observer sat immediately in front of the display at a self-determined distance.

Seven symbol sizes were included in the analysis: 2/16", 3/16", 4/16", 5/16", 6/16", 7/16", and 8/16". At the lower limit (2/16"), all symbols were barely discriminable, exhibited extreme variability and were not included in the statistical analysis (Figure 41). The relative discrimination order of the four symbols did not conform to the ranks resulting from the earlier study. The cross remained the more discriminable and the half-circle the less discriminable. The circle shifted to the second most discriminable and the cross-within-circle shifted to the third position. The difference between the most discriminable pair and the less discriminable pair was independent of size level. The minimum size at which discrimination was not impaired was between 3/16" and 5/16"; at 1/8" there was an extreme increase in scanning time and errors of omission for all symbols. The size at which these symbols ceased to function effectively as radar symbols appeared to lie between 1/16" and 3/16" (Figure 41).

No definitive rank order resulted from judgements of discriminability. Symbols were not differentially susceptible to omission with the exception of the cross-within-circle at the 2/16" level.

In 1964, Honigfeld (Ref. 171) reviewed the literature pertaining to radar symbology and concluded that there has not been sufficient work done in choosing one shape code system, evaluating it and assigning meanings to it to allow for the making of specific recommendations on radar symbology. Honigfeld's efforts indicated that the various method of presenting stimuli (slide projector, tachistoscopes, viewers, etc., but not actual or well simulated CRT tubes) were not sufficiently analogous to actual radar operation to permit one to generalize the results to radar symbology. Honigfeld found very few studies that defined, let alone controlled for, such experimental factors as acceleration, humidity, temperature, air pressure or stress which are commonly found in field

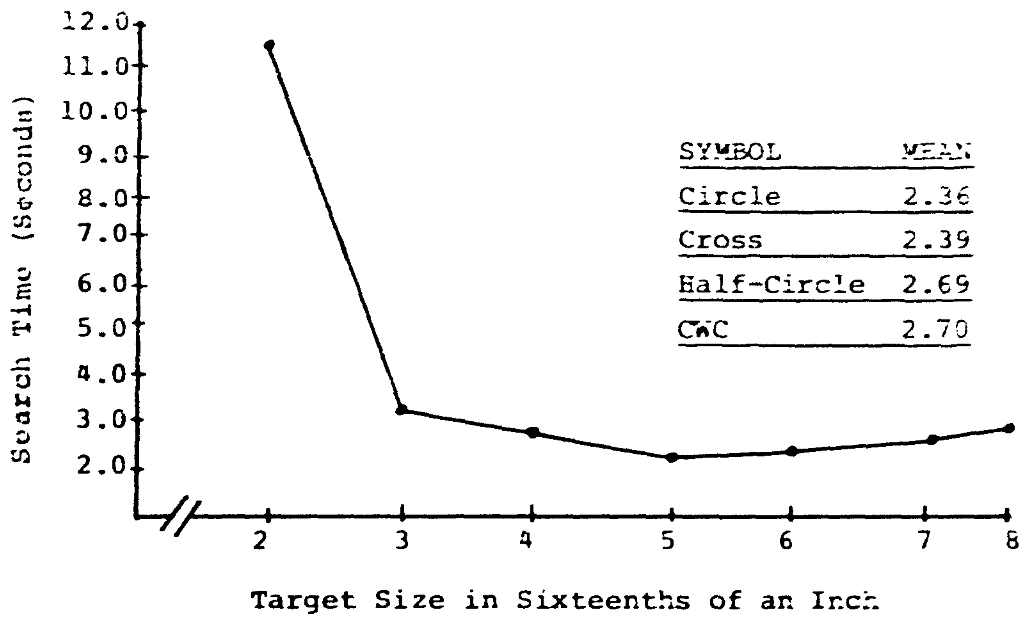


Figure 41. Scanning Time as a Function of Symbol Size. Curve Connects Mean Score at Each Size Level. (After Data from Dardano and Stephens, Ref. 100)

operating conditions. She recommended that the establishment of a standard radar symbology should await further experimentation and evaluation of these variables.

In 1969, Davis (Ref. 101) reviewed the literature and concluded that earlier studies were not relevant for application to radar situations. Many of the earlier conclusions she concluded were invalid because they did not take into account many of the operator-radar-scope variables found in the operational situation. Davis conducted a series of experiments which were intended to allow for these variables by dealing with the symbols in isolation, in confusion studies, symbol meanings and grouping. From the results of these studies, Davis drew up a set of recommendations for proper design of radar symbology.

In Experiment III, 20 subjects (visually screened civilian and military technical employees) from a previous experiment completed a paired-comparison meaning test (assigning a given meaning to a given symbol). Friendly, unknown, and hostile were explained to the subjects and after each meaning had been defined, the subjects were given a set of comparison sheets and a 3 x 5 card for use in comparing the symbols one at a time and then circling the symbol that best fit the meaning. After completing one meaning selection, the subjects were presented identical

material in different order and instructed to consider their use for a second meaning. Third meaning was treated in a similar manner. Selection without prolonged thought was emphasized. Data from this study is shown in Table 14.

The circle, oval and square were frequently selected as friendly and ranked low on the unknown and hostile list. The jet plane and the half square were ranked high as hostile followed by the vees and the apex up and down. The triangle, however, which is a form of the vee, did not follow a meaning trend. The intersecting arcs show the strongest trend as unknown, but beyond this there is no clear distinction.

The half-octagon was associated as an unknown target. Performance with the half-octagon was best when the half-circle with the enclosing diameter was omitted. Since the half-circle appears to be an "ideal" target, the half-octagon is not recommended. It is also undesirable because of degradation on the CRT. The intersecting arcs are also shown under the unknown column. It is possible that size differences would further improve this form within the recommended codes. Using it with the plus sign or the X should be avoided. This symbol has minimal effect on the circle, half-circle, pointer, and square. It is the best fifth symbol in the study.

The triangle was poor (as both hostile and unknown) in both time and errors. The pointer and the diamond probably interacted with it to degrade performance. Further changes in size might improve the triangle symbol.

The plus sign showed poor performance when paired with the X. It was recommended that one of these two symbols be rejected in the same code.

The data gave no evidence concerning the advantages or disadvantages of either linear or alphanumeric modifiers. The modifiers were considered in the study only in terms of interaction with the basic forms. The potential advantage of such modifiers should be further investigated.

In another experiment in the same series of studies (Experiment V, from Davis, Ref. 101), 10 new subjects were selected and visually screened and then familiarized with a set of figures similar to those used in the above discussed study. They were then presented with 10 sets of modified symbols (5 symbols in each set being devised or modified in accordance with the results of the four preceding experiments). The symbols were centered within a 1/4-inch radius on 3 x 5 cards (Figure 42). The five basic symbols (or suits) of a series appeared from 9 to 13 times in each deck of 55 cards (2 decks of cards being used for each subtest for a total 2-deck count of 22 for each symbol). While the test decks of cards were

Table 14. Total Occasion Each Symbol was Preferred for A Given Meaning Recorded for Each Symbol. (From Davis, Ref. 101)

Paired Comparisons - Totals

N = 20

	FRIEND		FOE		UNKNOWN		
	No. of Choices	Rank	No. of Choices	Rank	No. of Choices	Rank	GRAND TOTAL
1.	241	9.5	189	16	211	15	641
2.	131	22	285	4	201	17.5	617
3.	189	17	298	2	249	5	736
4.	213	4	240	10	212	13.5	665
5.	224	12	248	7	213	12	685
6.	148	21	293	3	210	16	651
7.	242	8	178	18	219	10	639
8.	250	5	242	9	230	9	722
9.	241	9.5	184	17	294	2	719
10.	206	16	201	14	263	4	670
11.	290	2	145	22	212	13.5	647
12.	163	20	250	6	237	7.5	650
13.	243	7	175	19	237	7.5	655
14.	173	19	261	5	295	1	729
15.	357	1	66	23	130	23	553
16.	266	4	198	15	201	17.5	665
17.	121	23	306	1	216	11	643
18.	247	6	246	8	279	3	772
19.	211	15	236	12	163	21	610
20.	269	3	152	21	162	22	583
21.	237	11	166	20	243	6	646
22.	217	13	237	11	170	20	624
23.	185	18	234	13	195	19	614

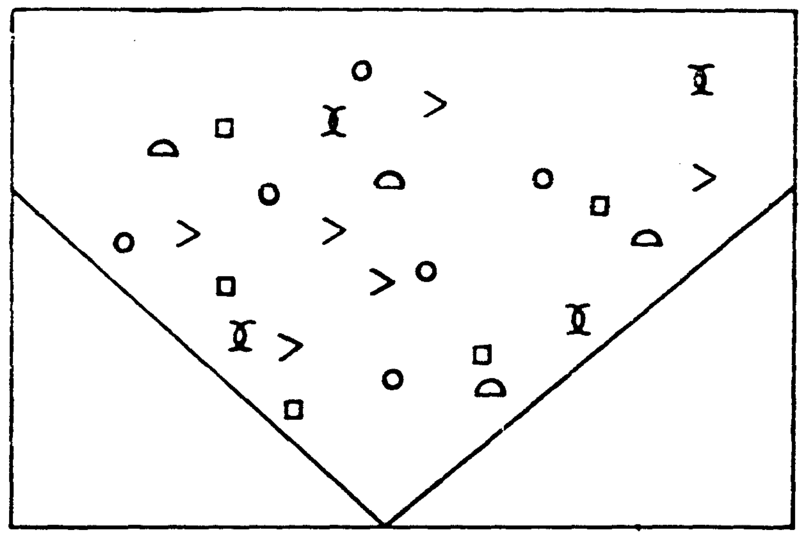


Figure 42. Arrangement of Symbols on 3 x 5 Cards for Experiment 4. (Davis, Ref. 101)

used and timed alternately, item sorts were inversely ordered to avoid possible recognition of the fact that each symbol appeared 22 times in the two decks. The subject was shown a specific symbol on a briefing card and asked to sort out all of the same symbols in his deck of cards. This procedure was then repeated for the second deck of cards in the subtest. A brief rest period was allowed and the subject was tested with the second set of symbols (second set of 2 decks of cards). Sorting error rate and the time required to sort out each of the target symbols were recorded as the performance measures.

The error rate and the sorting time are summarized in Table 15.

In general, the Friendly AST (air supported target) has been described by the circle. The results indicate that the circle was best when relatively smaller than the other targets. An ellipse within the code degraded performance with the circle.

The upper half-circle with enclosing diameter proved to be an excellent symbol, but performance with it was degraded with the presence of the open octagon and possibly with the triangle. Maximum efficiency was obtained when it was twice the size of the circle, pointer with the apex horizontal, intersecting arcs and either the square or the plus sign.

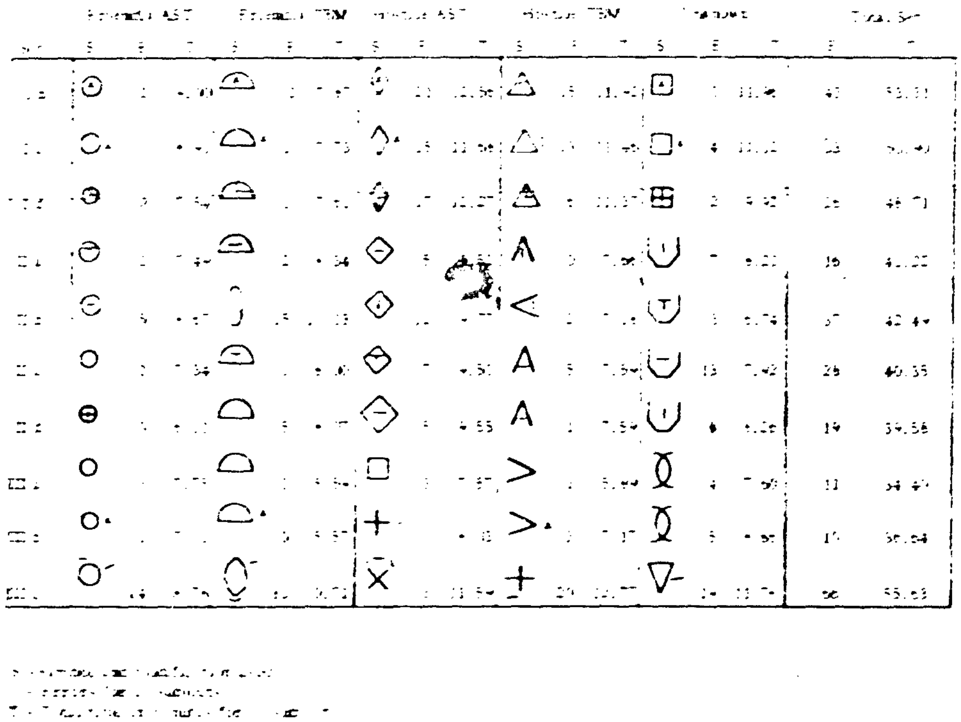


Table 15. Summary of Performance Showing Total Errors (E) and Time in Minutes (T) for Each Symbol (S). (After Davis, Ref. 101)

The ellipse was used in only two sets and in both the cases performance was inadequate with elongated times and increased errors. The circle and probably the diamond were the major contributing factors.

The diamond proved generally poor as a target in terms of time and error. It was extremely poor when compared with the triangle of nearly equal apical angle.

The pointer, or open triangle, with about 45° angle is an excellent target in either the horizontal or vertical orientation. It can be used with the circle, 90° diamond, half-circle, square, plus sign or intersecting arcs with little degradation. This symbol, along with the circle and half-circle, should be used in any code.

The square shows low errors, but its size relative to the circle is very important. The ratio of the diameter of the square to the circle should be 5/8.

The following general recommendations are based on the findings from the entire series of experiments:

1. Discernibility, or pure visibility, is not an adequate measure for selecting symbols to code mixed information. Two or more highly discernible forms may interact with resultant poor discriminability.

2. Any experimental method which presents symbols individually cannot demonstrate interaction between symbols. Sorting techniques are not suitable for code selection.

3. Experiments using black-on-white drawings representative of a coded, five-dimensional PPI display suggest the following tentative rules for code design:

a. Symbols should differ strongly in shape. Variations of a single form family such as the circle and ellipse are not desirable.

b. Redundant cues such as size difference may be advantageous.

c. Characteristics which are enhanced by a unique search method add to the saliency of an individual symbol in a code complex.

d. If several basic symbols are to be grouped within a major classification, a familiar resemblance may be desirable. Absolute discrimination of these basic forms requires that the resemblance be descriptive rather than perceptive. If absolute discrimination is not required, a single symbol should be adequate.

e. The most satisfactory five-dimension code in the current studies (Series IIIa) results in an average locating time of 0.80 seconds combined with an average error rate of 0.44 percent. The poorest code (Series IIIc) requires an average locating time of 1.34 seconds with 2.64 percent errors. This advantage reduces time to 59 percent and errors to 16 percent.

4. Further experiments using actual CRT displays are recommended before final standardization of radar symbols. A variety of phosphors and ambient illumination levels should be included.

5. Learning studies should be conducted to select ideal methods for increasing the informational value of the basic codes. Modifiers added to the basic symbols could confuse the total picture. A trade-off between the advantages of total information in a single symbolic unit and clean symbols with auxiliary readouts for additional information must be considered.

Conclusions

As stated above in the comments by Honigfeld (Ref. 17), too little meaningful work has been done in the area of display symbology to allow for the drawing of specific conclusions or recommendations applicable to electronically generated flight displays. The only unanimous opinion found in the reviewed studies was to the effect that further controlled research was required. Unlike the reviewed studies, however, real world (or appropriately simulated real world) testing is required which includes not only realistic viewing conditions, (fluctuating ambient illumination, observer and/or symbology motion, vibration, visual and motor time sharing) but also realistic observer task performance requirements (tracting, display searching, etc.). The inclusion of the above considerations is essential for further meaningful research on symbology for a given operational airborne display, not to mention valid generalizations from one display situation to another.

A brief review of the preceding results indicates that the triangle is the most efficient of the geometric forms tested in terms of search-time and accuracy (Gerathewohl, Ref. 134). The + is the most discriminable of the operationally tested symbols used by Dardano and Stephens (Ref. 100), followed by the circle ○, the cross within a circle ⊕ and the half-circle ∩, respectively. The circle, oval or square were most frequently identified as friendly aircraft (Davis, Ref. 101), while the jet plane Δ and the half-square ⊓ were most often called hostile. The half-octagon and the hooked curves were frequently identified as unknowns. The open triangle < proved to be an excellent symbol, regardless of its orientation (Davis, Ref. 101). Orientation of symbol had a slight effect on discrimination (Gerathewohl, Ref. 134).

Deese (Ref. 104) concluded that detectability varied as a function of symbol size, with the slope of the size/detectability relationship quite steep between $1mm^2$ to $2cm^2$ (symbol size) and leveling off after $2cm^2$. Dardano and Stephens (Ref. 100) found 3/16 to 5/16-inch to be the minimum size for field operations, but that at 1/8-inch or above performance fell off (scan time and error increased). Steedman and Baker (Ref. 321) recommend target size to be no less than 12' arc, but as much as 20' of arc, if feasible. Baker, et al. (Ref. 13), found that search-time and error increased as the number of irrelevant forms present increased. They indicated that subjects could "learn" what effects changes in resolution will have on targets.

Recommendations

The problem of optimum shapes for electronically generated displays is closely related to the resolution of the display itself. Symbols found to be excellent in terms of laboratory

(photographic black-on-white) performance may suffer significant performance degradation when subjects to electronic generation under operational conditions. Additionally, symbol types found to result in acceptable observer performance on one type of display system (CRT, for example) may produce unacceptable performance on another type of display (EL). Environmentally induced degrading factors (vibration, luminous fluxes) may reduce display resolution and symbol legibility at the same time. Current literature produces no data specifically addressing the above considerations.

The establishment of a set of standard, "worst case", viewing conditions would provide a basis against which to evaluate pertinent symbology data (CRT type of solid-state display viewed at 28 inches under ambient illumination ranging from 0.1 to 8,000 ft. Lamberts, with contrast varying from 10:1 up to 100:1, vibration ranging from 3 to 35 cps with amplitude ranging from 3/10 to 3 g's and with various visual and psychomotor task performance). Examination of various form families (i.e., triangles, circles, squares), symbol sizes with each of the above design variables independently varied (and varied in combinations) should provide the symbol shape-size combination that is most readily legible under the widest range of parameter variations that are likely to be encountered in flight. Additionally, these data should provide valuable design oriented trade-off relationships among all of the parameters examined and indicate the interaction effect of a number of the more significant variables.

Specifically, threshold symbol size is known to decrease as the luminous level is increased up to a maximum (about 100 ft. Lamberts, depending on other conditions). No data are found relating threshold symbol size to luminance at high luminance levels (above 1,000 to 2,000 ft. Lamberts). Likewise, minimum symbol size is known to increase in the presence of vibration, but the exact nature of this relationship is unknown. A systematic evaluation of minimum symbol size required for 100% legibility under increasing frequency and amplitude of vibration would establish this relationship. The relationship of symbol size and contrast could be examined in a like manner. A similar procedure would be followed for the evaluation of the other factors associated with symbol legibility.

In all of the above examinations, the observer performance measure would always be 100% symbol discriminability over all (or the greater portion) of the range of variation of the design variable being examined (or expected to be encountered in flight). On the other hand, the values derived (symbol size, for example) could not be inordinately large because of possible interaction effects with other parameters (reduction in the amount of other information that could be presented).

COLOR CODING

Introduction

Possibly the most difficult and controversial aspect of visual display encoding and one that has produced considerable literature is that of color coding. This situation is compounded by the fact that the exact physiological nature or basis of color perception is still only hypothesized. The retinal cones are generally regarded as the color sensitive receptors, but the precise manner in which they function is still being investigated. No single theory is completely acceptable, even today. However, certain empirical procedures have been evolved which are useful in describing and even predicting the phenomena of visual color and constitute the basis of modern colorimetric procedures.

Luxenberg and Kuehn (Ref. 226) conclude that color experiences are more than simple sensations elicited by certain stimuli. Color perception occurs in various modes as for example when the observer is aware of a surface that glows, glitters, appears dull, transparent, or reflective in nature. Most visual display systems usually involve more than one of these perceptual modes. Of the various modes, aperture color appears to be one of the more important in visual display design. Aperture color is usually seen as being non-object connected; that is, it appears as if it were filling a hole in a surface. There are three attributes associated with aperture color, and they are correlated to some extent with the physical characteristics of light. These consist of brightness, hue and saturation which are the response correlates of luminance, wavelength, purity and duration. These three attributes are of primary concern in the design of colored visual displays. Object colors and their properties of reflectance, volume, form, transmittance, etc., are relevant, but only indirectly.

Wulfeck (Ref. 363) concludes that the sensation of color consists of at least the three factors listed above and that these are complexly related to the physical characteristics of the stimulus and to the illuminant under which it is viewed. He describes brightness as being closely related to the rate of transfer of luminous energy, that is the lumens per sterdians per unit of area (lamberts). The hue (color) of an object is closely related to the dominant wavelength of the light being emitted or reflected from its surface. The saturation of a color (the purity) is related to the amount of white light mixed with the hue or color. The latter is dependent to a large extent upon the type and the amount of illuminant present.

It must be noted that the specification of a color is usually done so in terms of all three of its attributes. Since all of these interact, care must be exercised when measuring one component to keep the other two as nearly constant as

possible. For this same reason, the display designer must take into consideration the other two attributes of a selected color when assigning it to a visual display. He must choose colors that will be bright enough to be legible under all conditions expected to be encountered while viewing the display. This includes both the amount and types of illumination to be encountered. As Wulfeck (Ref. 363) points out, important markings on some aeronautical charts simply vanish under red light.

Until most recently, it had been possible to account for nearly all the aspects of color vision by one of two basic theories of color vision. With very few exceptions, all the important theories of color vision could be grouped into two basic categories; the trichromatic school of the Young-Helmholtz theory or in the opponents-process concept of Herring. Schroeder (Ref. 291) evolved a theory which does not require different kinds of cones or photochemicals, but accounts for color by having three identical receptors positioned at appropriate points along the outer segment of each cone. Color discrimination is accomplished by the interference of reflected waves with incident waves from an object. This theory, however, is entirely physical in nature and does not account for the physiological or psychological phenomena or process. Boynton (Ref. 39) proposed a theory that attempted to account for the physics, physiology and the psychology of color vision by assuming three types of photo pigments distributed among five types of cones. He concludes, however, that the process of color vision will not be fully understood until "electrophysiologist, probing into the brain with his electrodes, has found the electrophysiological substrate of conscious color experience". Several other attempts have also been made, but none have successfully accounted for all the parameters of color.

Color may be perceived as chromatic or achromatic. Chromatic colors are those colors that elicit hues; that is, colors with wavelengths that elicit the primary sensation of hue (e.g., red, blue, green). The chromicity of a color refers to the particular aspect of the color described by its dominant wavelength and purity (purity is the property that evokes the sensation of saturation). The discrimination of hue is an individually sensitive process wherein the observer may be able to detect a hue difference, but is unable to describe the difference or assign a name to it. Additionally, small luminance variations can obscure the detectability of hue shifts. With all other variables being held constant, the detectability of hue change also varies with the portion of the color spectrum being altered. Osgood (Ref. 259) states that there are four spectrum positions at which maximal differential sensitivity occur. These positions are generally regarded as being: 440 (blue), 485 (green), 575 (yellow), and 640 nm (red).

Achromatic colors are referred to as neutrals or grays in that their dominant wavelengths do not elicit the sensation of hue. Without the quality of hue, achromatic colors do not have the attribute of saturation which Burnham, Hanes, and Bartleson (Ref. 55) describe as a color's degree of departure from an achromatic color of the same brightness. Luminance changes also considerably affect saturation. At a level above some optimum (50-100 ft. L), a decrease in saturation of chromatic colors occurs until at extremes a total desaturation or achromicity is approximated. In this region of absolute luminance thresholds, all colors (with the exception of red (640 nm and up) elicit achromatic sensations. Again, the luminance level necessary for maximum saturation is wavelength-dependent. However, colors which elicit greater saturation require less luminance to appear maximally saturated (blues, reds, and purples are in this category). Yellows and green-yellows require comparatively high luminance levels to appear saturated.

As is evident here, colors by themselves are complex stimuli with interrelations between luminance, purity, dominant wavelength, and of course, the psychophysical response. Basic knowledge of these interactions would be beneficial in establishing a true multidimensional coding system. Bishop and Crook (Ref. 30) working towards such a code discovered that the interdependence of these dimensions becomes more apparent with small stimuli. Jones (Ref. 186) concludes that systematization of brightness, saturation, and hue is still far from complete and that much work remains to be done in this area.

The investigation of color codes has become more pronounced in recent years with the advent of and increasing reliance on computer generated and other complex display systems. But even in these modern systems, man is still the primary analyst of the information presented, and ways and means of improving his efficiency are constantly being sought. Even under optimum conditions, the amount of information that the human can process within a given period of time reaches an asymptote as the amount of stimulation increases. As Miller (Ref. 237) pointed out, man's channel capacity is rather small. The introduction of independently variable attributes of a code selected from a single continuum may increase the amount of information that can be transmitted, up to certain limits. In this respect, color coding holds great promise in the more complex display situations.

The brief discussion thus far enumerated but a few of the many parameters that must be considered in the application of color to visual displays. Add to these such basic considerations as: the effects of brightness, size, and nature of light source, the nature of the operator's task, the interaction effect of the colors employed, the use of multidimensional codes, and the cost of generating color and its reliability, and the scope of the task is widened even further. It is beyond the scope of this

report to deal extensively with these and the many more variables associated with color coding. Indeed, it is not even certain that it would be of value to do so. This section, therefore, will limit itself to addressing three problems of color coding of visual displays. This is by no means an attempt to relegate the many other variables to positions of lesser importance, but merely an effort to concentrate attention on several of the factors directly applicable to visual displays. These factors are:

1. Hue Alphabet Size: What is the maximum number of colors that can be absolutely discriminated under operational conditions? This question takes into account such factors affecting discrimination as: symbol size, ambient and background illumination, degree of registration (or misregistration of color), luminance levels, purity, and brightness.

2. Advantages of Color Codes: Under what conditions is the use of color coding more efficacious than other means of coding information? This question must take into account: the nature of the information presented, density of the information presented, nature of the operator's task, the criticality of the information, and the trade-off values involved.

3. Disadvantages of Color Coding: Are the advantages achieved through the use of color warranted in light of the cost of production? Here we are concerned with the problems of the initial cost of generation, maintenance and reliability of color, and the need to use this method. Additionally, some of the disadvantages of color coding must be considered.

These three "questions" form the basic structure for the following review.

HUE ALPHABET SIZE

Considerable research effort has been directed towards establishing the number of different spectral hues which can be used together effectively. Ketchel and Jenney (Ref. 206) conclude that the number depends upon the brightness and size of the light source, the nature of the observer's task, and the particular colors used. If only relative judgements are required of the observer, the number of discriminable spectral hues is quite large. Rizy (Ref. 278) cites an unpublished report by Halsey (1962) who estimates that under ideal conditions the total number may be as high as ten million. But, Halsey goes on to say that under poor conditions and considering stringent speed and accuracy demands placed on the observer as well as the realistic limitations placed on operational color generating equipment, the number of discriminable colors may be as low as three.

Wulfeck (Ref. 363) suggests that with good illumination (not specified) and saturated colors, some 128 hues could be comparatively discriminated by observers. He cautions, however, that the ability of the eye to discriminate colors varies with the different portions of the color spectrum being dealt with. The eye's discrimination is greatest at two separate points along the spectrum, in the region of blue-green wavelengths and yellow wavelengths (see Figure 43). At these two points, wavelength differences as small as one millimicron can be discriminated as separate hues. At the red end of the spectrum, however, the difference must be as great as 20 millimicrons in order to be discriminated as separate hues. He also notes that the number of colors that can be discriminated on an absolute basis is much smaller than the 128 figure given above.

Most display-oriented experimenters prefer to use absolute judgements as the criterion of discriminability. Baker and Grether (Ref. 12) determined that with a brightness of 1 millilambert and with a visual angle subtense of at least 45 min. of arc, the ten hues shown in Figure 44 can be correctly identified nearly 100% of the time.

If white is included, the number of absolute identifiable hues is 11. This number has been confirmed by several other sources (Halsey and Chapanis, Ref. 369; Muller et al., Ref. 250; Morgan et al., Ref. 247).

Jones (Ref. 186) concluded that the findings on absolute hue judgements were "in sharp contrast" to research on comparative judgements. Wright (Ref. 367), in a comparative discrimination study, found that observers could comparatively discriminate approximately 150 stimulus hues. Hanes and Rhodes (Ref. 157) attempted to train observers in order to increase the number of absolutely discriminable surface colors. After extensive practice their observer was only able to identify 50 colors, but this skill was readily lost without practice. (It should be noted that the Munsell chips used by Hanes and Rhodes varied in saturation and lightness as well as hue).

The size of an unequivocal hue alphabet has been determined by the number of points along the wavelength continuum that are accurately discriminated by the visually normal observer. This number of discriminable hues not only defines the amount of information that can be transmitted per stimulus, but also indicates some of the qualifications of the hue as a coding means. Probably one of the first investigations of the hue continuum using this method of absolute discrimination (judgement) was carried out by Halsey and Chapanis (Ref. 369). They used luminous spectral hue (which did vary in saturation) in developing four alphabet sizes ranging from 10 stimuli to 17 stimuli. The test spots used were about 45 minutes of arc and had luminances of 28 candles per square meter. The background luminance was 24 candles per square meter.

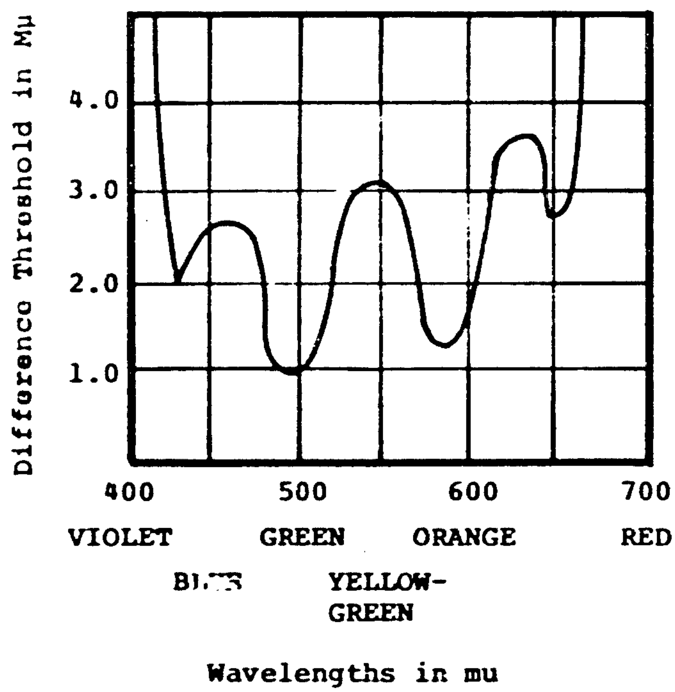


Figure 43. Smallest Difference in Wavelength that can be Detected as Different in Hue Using the Comparative Method of Discrimination. (After Wulfeck et al., Ref. 363)

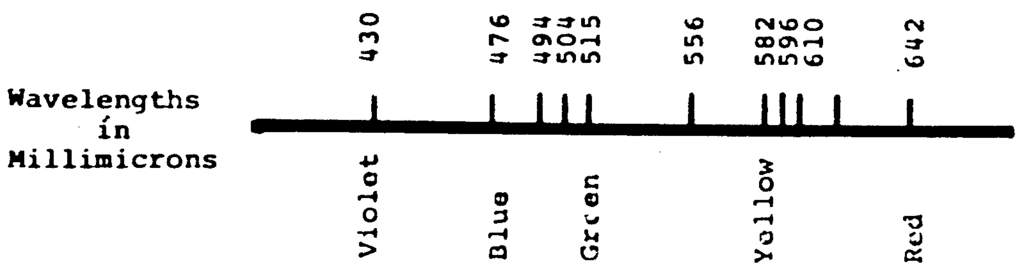


Figure 44. The Ten Absolutely Identifiable Spectral Hues Suggested by Baker and Grether. (Ref. 12)

Table 16 summarizes the findings of this study. It can be seen that the 10 stimuli alphabet was identified with the greatest accuracy (average of a 2% error rate). The error rate increased as a function of the size of the alphabet.

Conover and Kraft (Ref. 87) and Conover (Ref. 85) extended the work of Chapanis and Halsey to surface hues. They attempted to determine the maximum number of absolutely identifiable hue stimuli and to construct a scale of equally discriminable hues. Ten subjects viewed 25 hues in random order, masked by one of three neutral backgrounds. The color patches were presented through a three degree aperture of a neutral mask and were viewed under 21.4 ft-candles of 6800° K illumination.

Table 16. Summary of Data Obtained with Absolute Judgement of Spectral Colors. (Chapanis and Halsey, Ref. 369)

Number of Colors in Set	Percent of Responses Correct	Average Errors of Judgment (Per cent of Range)
17	75.3	2.6
17	69.4	2.9
17	72.4	2.7
15	97.4	1.8
15	92.2	2.1
15	94.8	1.9
12	99.2	2.1
12	92.5	2.6
12	97.5	2.2
12	93.3	2.5
12	95.6	2.4
10	97.0	2.7
10	98.0	2.6
10	97.5	2.7

The authors found that the number of absolutely discriminable hues varied from 5 to 16 , depending upon the individual being tested. Under ideal viewing conditions, half of the subjects tested could discriminate without appreciable error nine maximally saturated surface hues. They suggest that this be the maximum number used in displays. If the operator is to make absolute judgements on the basis of hue alone, then eight should be the maximum number used to minimize error. From their results, the authors recommend the 5, 6, 7, and 8 hue alphabets shown in Table 17. They caution, however, that these colors are for surface hues alone. Care should be exercised in extrapolating these results to CRT type or self-luminous displays without further validation. The smaller alphabets should be used where applicable to improve identification accuracy. They suggest that not more than six hues be employed when desaturated self-luminous hues are used. If these are to be viewed under degraded conditions, no more than five should be used.

The achromatic series of hues were deliberately omitted from the recommended colors (white through black) because they could not accurately be absolutely discriminated under less than ideal viewing conditions. They estimated that the average person's ability to make reliable absolute judgements of lightness differences is limited to not more than three steps - white, gray and black.

Bishop and Crook (Ref. 30) conducted a series of studies to determine the number of colors which could be absolutely identified by subjects with normal color vision when viewed against various colored backgrounds. Additive mixtures of light were passed through narrow-band and Illuminant-C filters and projected onto a viewing screen by a device which permitted independent control of the target and background characteristics. The stimulus parameters of hue, luminance level, purity, target size, and target shape were varied, and the results of these factors interacting with training and the presence of distracting tasks were studied.

Eight subjects with varying degrees of training served in the study. All subjects had normal color vision. The 28 stimuli were presented on a 0.5 ft. Lambert white background. Mean ambient illumination was 0.2 ft. Lamberts. The subjects viewed the 0.5 inch stimulus from a distance of 20 inches (which subtended a visual angle of 1 degree, 26 minutes). No time limit was placed on the stimulus presentation but the subjects were instructed to avoid excessive delays. Response times varied widely, with an estimated model time of 10 seconds. Purity levels of the colors were varied from 10% up to the maximum shown in Table 18. A purity of 70%, however, was assumed to be the best that could be obtained in operational systems and this figure was used in the concluding recommendations. The target

Table 17. Recommended Color Alphabets: Chart A for 8 Hue Alphabet, Chart B for 7 Hue Alphabet, Chart C for 6 Hue Alphabet and Chart D for 5 Hues. (After Conover and Kraft, Ref. 87)

Book Notation (Munsell)	Trilinear Coordinates x	y	Dominant Wave Length	Munsell Renotation H V C
Chart A				
1R	441	234	493.0^{c}	1R 5.06 10.3
9R	508	363	596.6	9.5R 5.93 11.5
1Y	477	458	579.8	2Y 7.12 11.6
7GY	374	482	565.6	5GY 6.48, 8.3
9G	241	365	499.7	10G 4.88 6.8
5B	193	241	482.8	6B 4.00 7.0
1P	2[illegible]	171	420.0	1.5P 3.74 11.1
3RP	357	248	510.0^{c}	2.5RP 4.90 9.5
Chart B				
5R	481	324	610.0	5R 5.13, 10.6
3YR	525	405	589.8	4YR 6.28, 12.4
5Y	448	477	575.5	6Y 7.63, 11.0
1G	314	466	552.3	10GY 5.83, 8.2
7BG	216	313	490.5	7BG 4.67, 6.7
7PB	201	165	470.1	7PB 3.48, 10.3
3RP	357	248	510.0^{c}	2.5RP 4.90, 9.5
Chart C				
1R	441	294	493.0^{c}	1R 5.06, 10.3
3YR	525	405	589.8	4YR 6.28, 12.4
9Y	429	488	572.7	9.5Y 7.39, 10.2
5G	257	406	513.2	5G 5.09, 7.6
5B	193	241	482.8	6B 4.00, 7.0
9P	318	209	547.2^{c}	8.5P 4.41 11.2
Chart D				
1R	441	294	493.0^{c}	1R 5.06, 10.3
7YR	496	430	584.5	8YR 6.45, 11.2
7GY	374	482	565.6	5GY 6.48, 8.3
1B	207	287	487.6	10BG 4.29, 6.3
5P	284	184	559.6^{c}	5.5P 4.16 12.4

Table 18. Colors and Purity Levels Used by Bishop and Crook. (Ref. 30)

Color	Catalog Designation	Dominant Wave Length	Excitation Purity
Red	Corning 2-78	630	100%
Orange	Wratten 72B	606	100
Yellow	Corning 3-110	588	100
G-Yellow	Wratten 73	574	100
Y-Green 1	Corning 4-102	552	100
Y-Green 2	Wratten 74	538	96
Green	Corning 4-105	521	82
B-Green	Corning 4-104	500	92
G-Blue	Wratten 75	492	88
Blue	Corning 5-60	461	97

luminance level was varied (1, 10, and 100 ft-L) and the target size was varied (0.06 inch, 0.12 inch, 0.50 inch and 2.0 inch).

Bishop and Crook concluded that learning played an important part in the discrimination of a large number of colors. Although not specifically studied in this series of experiments, the results indicated that the basic set of 28 stimuli displayed on a white background could be learned in from 10 to 14 trials. It was also found that conditions which tend to attenuate the colors produced poorer scores. It was found, however, that the subjects could learn to identify colors with purities as low as 50% presented on colored backgrounds with purities as high as 50% with a moderate amount of practice. Learning beyond this stage was deemed too costly for the results produced.

The three luminance levels used in this study (1, 10, and 100 ft. L) were all identified with 'satisfactory' accuracy. Luminance levels of above 100 ft. L were not examined because of the limitations of the generating equipment and the introduction of the additional parameter of glare.

With a small amount of additional training, the subjects could reduce identification error to zero using colored backgrounds of not more than 50% purity. (See Graph D, Figure 45). The subjects reported that the colors looked different on the colored backgrounds, but the results reported suggest that the tasks were not much more difficult with the colored backgrounds

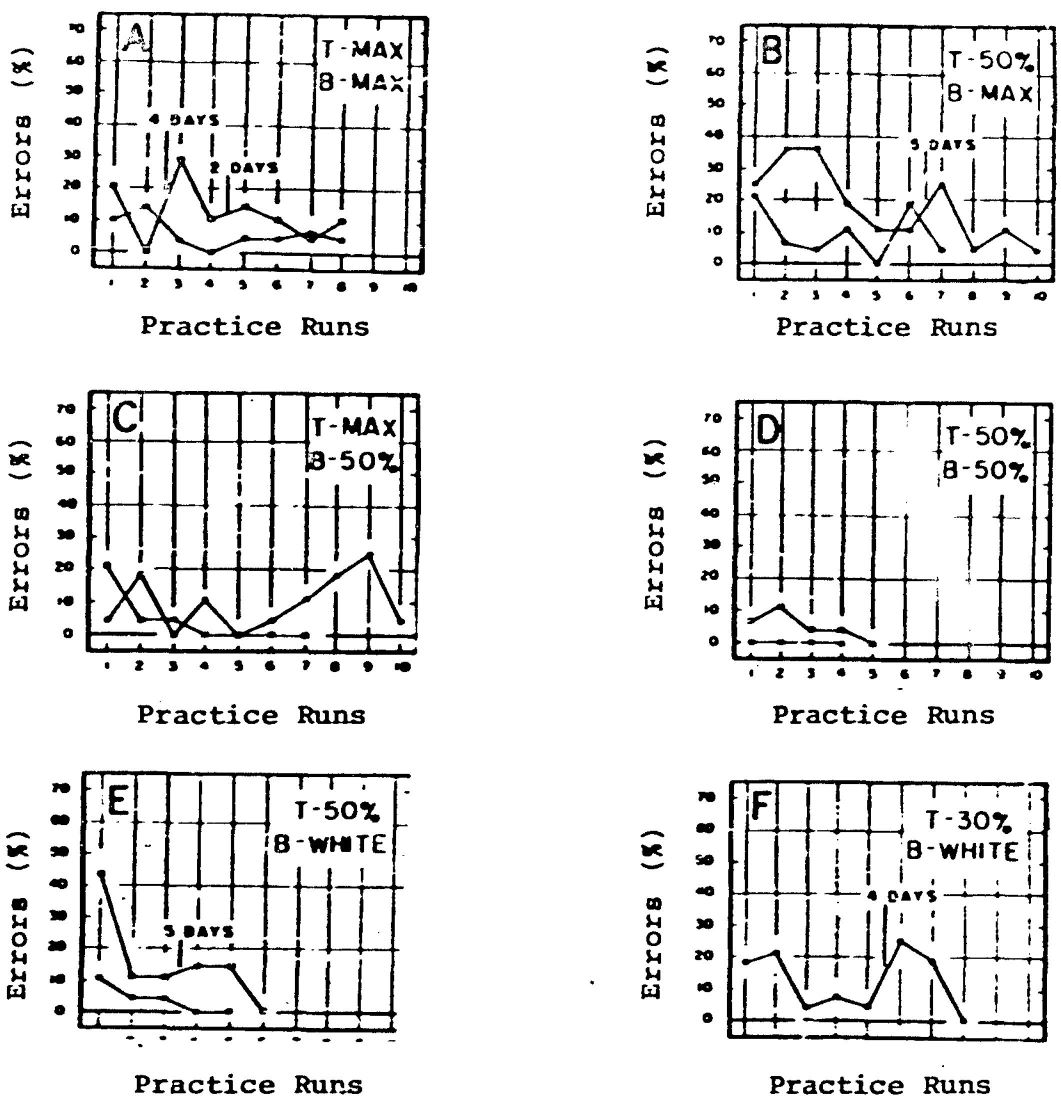


Figure 45. Percent Error in Color Identification as a Function of the Number of Practice Runs. (Averaged for All Subjects) for Selected Target (T) and Background (B) Purity Combinations (After Bishop and Crook, Ref. 30)

than with the white. Additional examination of this problem of colors appearing to be of different colors on colored backgrounds is required before equally discriminable color alphabets could be developed for different backgrounds.

In conclusion, the authors make the following recommendations based on the results of their experiments:

There are probably 50 to 70 colors varying in hue, purity, and luminance in the range between 2 and 200 times the background luminance, which can be identified absolutely with extensive training under laboratory conditions. There are approximately 30 colors usable in an operational system, assuming moderate training and reasonably favorable working conditions. Identification of 28 colors at maximum purity, varying in hue, and in luminance in the above range, against a white background, can be learned in 10 to 14 practice runs through the set. Such factors as colored backgrounds and reduced target purity increase the difficulty of identification. After targets at maximum purity against a white background have been learned, targets at no less than 50% purity combined with colored backgrounds of no more than 50% purity can be learned with a moderate amount of additional practice. More severe conditions require extensive training. About 10 hues (with white) are likely to be usable in an operational set, 3 luminances, and 2 purity levels (other than zero purity), though only about half of the possible combinations can be safely used without excessive training. Background purity interacts with target luminance, high purity producing increased errors at the lower luminances. Colored targets at luminances below that of a colored background cannot be identified with satisfactory accuracy. Target size in the range from 0.12 inch (21' of visual angle) to somewhere above 0.5 inch (5^{o} 4') is not a significant factor, but a decrease in diameter of round targets from 0.12 inch (21') to 0.06 inch (10') impairs identification. Conditions which appear to interfere with the subjective reference standard, such as distracting tasks, lapse of time, and increase in the number of items tested in a set, tend to impair color identification.

Meister and Sullivan (Ref. 232) reviewed the literature on coding and recommended the colors presented in Table 19 for use in the design of visual displays. Examination of this table reveals that the recommendation correspond rather closely with the distribution suggested by Baker and Grether (Ref. 12). Meister and Sullivan did not indicate the sources they used as the basis of their recommendations.

Morgan et al. (Ref. 247) makes the following recommendations for color coding targets to be detected against a nonuniform background:

Table 19. Color Recommendations by Meister and Sullivan.(Ref. 232)

Recommended Chromatic Colors

Color Name	Munsell Book Notation	Chromaticity Coordinates	Dominant Wavelength Nonometers	Federal Spec. 595 Equivalents (paint chips)
Purple	1.0 RP 4/19	x - .2684 y - .2213	430	27144
Blue	2.5 PB 4/10	x - .1922 y - .1673	476	15123
Green	5.0 G 5/8	x - .0389 y - .8120	515	14260
Yellow	5.0 Y 8/12	x - .5070 y - .4613	582	13538
Orange	2.5 YR 6/14	x - .6018 y - .3860	610	12246
Red	5.0 R 4/14	x - .6414 y - .3151	642	11105

Recommended Achromatic Colors

Color Name	ISCC-NBS Symbol	Munsell Value	Chromaticity Coordinates	Federal Spec. 595 Equiv.
Black	Bl	N1.0 or lower	x - .3151 y - .3425	17038
Gray	Gy	----	x = .3100 y = .3160	16187
White	White	N9.0 or higher	x = .3137 y = .3222	17886

1. Choose a color that contrasts most with the colors in the background.

2. Choose a brightness that differs as much as possible from the background. Pick white or bright colors for dark backgrounds, and visa versa.

3. Use a fluorescent color for targets against a dark background.

4. Use as large an area of solid color as possible. Do not use strips or checks; patterns like these are not visable at small visual angles; they only fuse and reduce the contrast of the target against the background.

5. If the target has to be seen against various kinds of background, have the target in two contrasting colors, dividing the target so as to make the two areas of solid color as big as possible; one or the other of the two colors will contrast with most backgrounds. Good pairs of colors for this purpose are the following:

white and red

bright yellow and black

bright yellow and blue

bright green and red.

Summary

This brief summary of some of the more important works dealing specifically with hue alphabet size allows for the drawing of the following conclusions:

1. No definite alphabet size can be specified. An average drawn from the reports reviewed shows the size to be between 8 and 12 hues, the exact size varying with the viewing conditions, the individual viewer, and the amount of information that is required to be displayed (Table 20).

2. The specific hues recommended varied from study to study. This is a good indication that such important variables as illumination levels, individual differences, and display mechanisms all play a significant part in the perception of color.

3. Only brief references have been made in connection with color on CRT type displays. No significant research has been uncovered directly dealing with the use of color coding on CRT displays under the operational conditions experienced in airborne environments.

Table 20. Summary of Recommendations.

Color - Absolute Discrimination

Authors	Display Type	Min. No.	Max. No.	Recommended
Meister & Sullivan Ref. 232	Slides CRT Surface Hue	5 3 7	7 5 11	
Baker & Grether Ref. 12	Spectral Hues		10	If white is included no. is raised to 11 hues absolutely discriminable
Halsey & Chapanis Ref. 369	Spectral Hues	10	17	10 max. for 98% accuracy
Conover Kraft Ref. 87	Surface Hues	5	8	8 max. no. absolutely identifiable by most of population with acceptable accuracy
Bishop Crook Ref. 30	Spectral Hues		10	10 hues (with white) are likely to be usable in operational situation
Muller et al. Ref. 250			10	Developed equally discriminable alphabet
McCormick Ref. 230	Not Specified		8	Adopts Conover & Kraft's recommend.
Luxemberg Kuehn Ref. 226			11	10 colors plus white can be correctly identified nearly 100% of time
Roth (Ed) Ref. 286			9	Adopted from list by Baker & Grether
Gebhard Ref. 127		8	12	Colors not specified

In light of the above, the recommendations made by Conover and Kraft (Ref. 87) regarding the generalization of color coding recommendations to areas other than those prescribed in individual experiments certainly appear valid. Due to the extreme interaction between the human visual process and the parameters associated with light and color, it would be impossible to predict performance with any degree of certainty without direct empirical validation with the systems to be employed.

ADVANTAGES OF COLOR CODING

Unlike the preceding section dealing with the size of the hue alphabet, more conclusive data have been found relating to the utility of color as an aid in display information coding. From the review that is to follow, several general conclusions can be seen to emerge:

1. Color codes are best for location or attention gaining.

2. Color coding is less efficacious than other coding methods for identification tasks.

3. Human performance is improved with color codes when the color is used in conjunction with other coding methods (alphanumerics, or geometric shapes).

4. The use of color in coding provides an additional dimension for the presentation of information.

5. The sensation of color is common to all color-normal observers and therefore requires little additional training.

The following review has turned up little in the way of pertinent information relating to the effectiveness of various colors for coding. Several studies have examined the order of discriminability of several commonly used coding colors.

Snadosky et al. (Ref. 318) conducted an experiment in which they determined the relative order of absolute discrimination of a number of colors. Using a three color additive technique, 36 alphanumeric symbols were projected simultaneously in seven colors (red, green, blue, yellow, magenta, cyan, and white). Six male subjects with 20/20 normal color vision were used in the study. Six randomizations of an alphanumeric matrix were programmed, generated on a character tube, and photographed on 70-mm Kalvar film for a total of 252 symbols arranged in an 18 x 14 matrix. The subjects viewed the screen from approximately 18.5 feet away. The symbols on the screen had a height of 1.75 inches (27 min of arc). Ambient illumination falling on the screen was about 0.01 ft.L. The color misregistration ranged from 33% to 200% (see next section for definition).

The results of their study indicate the relative discriminability of the colors examined to be as shown in Table 21 and response time as shown in Figure 46.

Table 21. Relative Discriminability of Colors Examined. (After Snadowsky et al., Ref. 318)

Color Used			Relative Discriminability
Red			93.75%
Yellow			98.30%
Blue			83.30%
Magenta	-	(Red + Blue)	95.45%
White	-	(Red + Blue + Green)	98.48%
Green			97.73%
Cyan	-	(Blue + Green)	98.00%

The negligible amount of ambient illumination and the relatively high contrast ratios achieved in this study would almost never be obtained in operational airborne display systems. While it would be difficult to generalize these findings, they do help to indicate a trend that will develop over the next few studies.

Rizy (Ref. 278) in a follow-up study to the one performed by Snadowsky et al, produced somewhat different results. He projected a total of 252 symbols arranged in six different 18 by 14 matrix formats onto a front projection screen (6 ft. x 8 ft.) located a distance of 20 feet from the projector. Six subjects were seated approximately 18.5 feet from the screen (individually) and viewed the symbols which were exposed for 15 seconds. The ambient illumination reflected from the screen was 0.09 Ft. Lamberts while the display color brightness ranged from 0.12 ft.L for the dimmest blue to 0.70 ft.L for the brightest white character. The maximum allowable misregistration was 33% of the strokewidth. The letter heights on the screen were approximately 1.75 inch (27 min of visual angle) which was well above the generally accepted lower limit.

Rizy found red to be superior for color coding, followed by yellow, magenta, and white which were statistically equivalent. These were followed respectively by cyan, blue and green (see Figure 47). He suggests that the high discriminability of yellow can probably be explained by the nature of the response

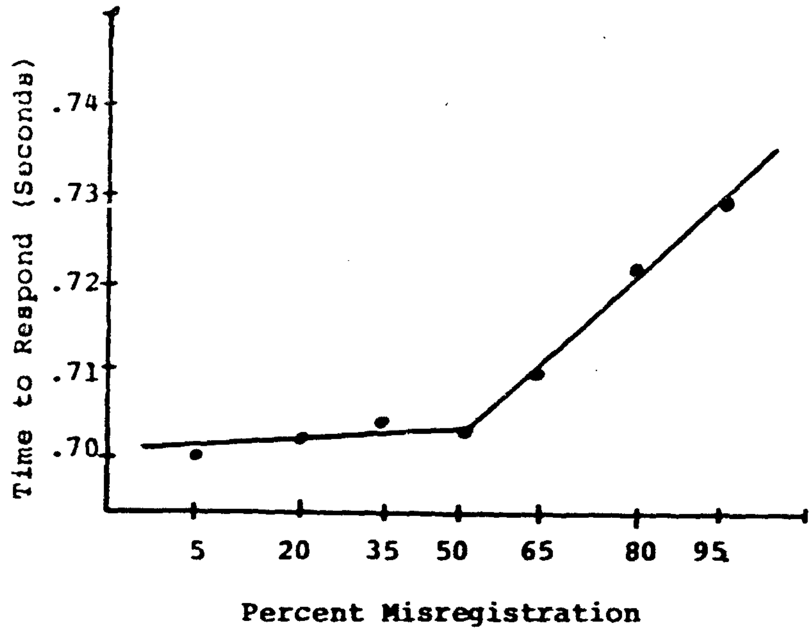


Figure 46. Response Time as a Function of Percent Misregistration. (After Snadowsky et al., Ref. 318)

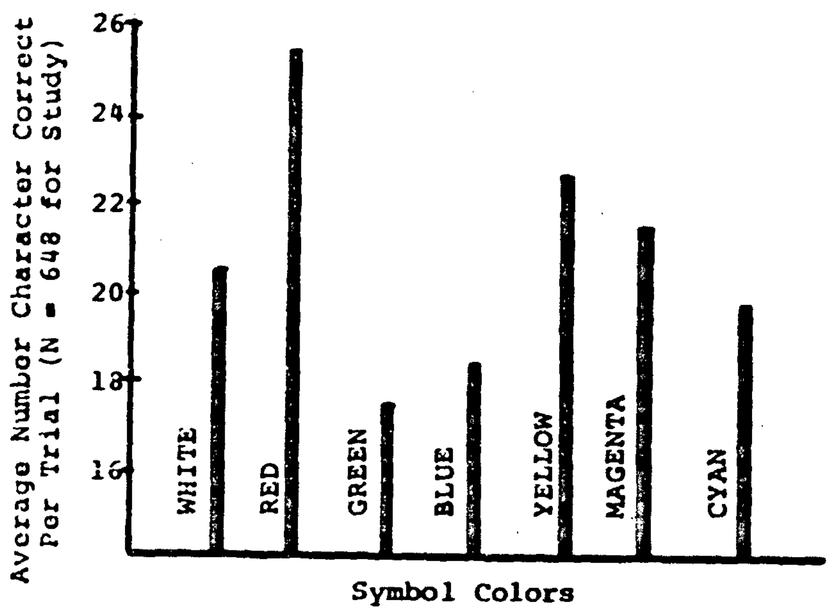


Figure 47. Subject Performance for Symbol Colors Averaged Over All Conditions. (After Rizy, Ref. 278)

of the human eye (visual mechanism) to the wavelength characteristics in this portion of the color spectrum (see report section on visual acuity). He found the relatively low rank of the green harder to explain, since it and yellow are the brightest appearing colors. Green had long been considered an excellent color in terms of visibility and discriminability. He suggests that in this case, perhaps the green appeared too bright and this led to color confusion. Again, due to the sensitivity of the eye, the brightness (intensity) of the green could be reduced considerably without impairing legibility.

The author predicted apriori that the least bright of the colors would be omitted most often because of the assumption that the brightest colors would be seen more readily than dimmer colors. This, however, was not the case. Figure 48 shows the almost the exact opposite was found in this study. The least bright colors (blue and red) produced the fewest omissions while the brightest (white) produced the most omissions. Rizy concludes that symbol brightness alone is not as effective in attracting attention as differences in both brightness and hue.

Finally, the results indicated that blue, although omitted the least, was most often misidentified. The white and yellow symbols were least often misidentified. He concluded that this was a good measure of the code legibility and is directly dependent upon the brightness of the symbol color.

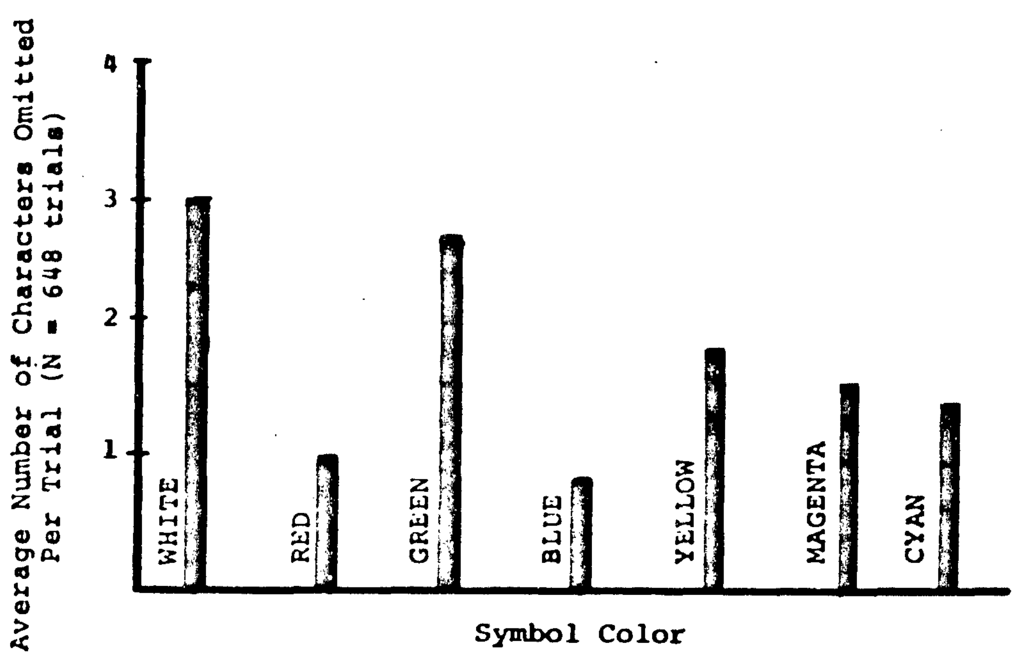


Figure 48. Number of Omissions as a Function of Color. (After Rizy, Ref. 278)

These two studies show some correlation in the results and some deviations. It must be remembered, however, that they were both conducted under low-light level conditions and the results of both could be expected to vary considerably with substantial increases in the illumination level. Solid research in this area is required prior to the drawing of any conclusions or recommendations. Some of the following studies indirectly deal with this problem.

Eriksen (Ref. 116) conducted an experiment to determine the speed with which various objects could be located on a visual display under the following conditions:

1. When various classes of objects on the display differed from one another on only one of four visual dimensions of hue, brightness, size and form.

2. When the classes of objects varied from one another on two or three of these dimensions (Table 22).

Table 22. Visual Dimension Variations Used in Experiment. (After Eriksen, Ref. 116)

The Seven Classes of Objects Used Within the Four Dimensions.

Visual Dimension Variation	Dimensions			
	Hue*	Form	Bright-ness*	Size (In.)
Target	R 5/6	Circles	N 1/	4/8
2	YR 5/6	Hexagons	N 7/	5/8
3	Y 5/6	Diamonds	N 6/	6/8
4	GY 5/6	Triangles	N 5/	7/8
5	G 5/6	Crosses	N 4/	8/8
6	BG 5/6	Stars	N 3/	9/8
7	B 5/6	Squares	N 1	10/8

* Munsell notation.

A total of 60 subjects viewed the 3 foot square display screen (viewing distance not specified) which was perpendicular to the subject's line of sight. Illumination levels were not specified.

The results (Table 23) show that the location times obtained by compounding the dimensions failed to show any consistent advantage over the single dimensionsal location times. Hue-Form is the only case where a compound dimension gives a slightly faster location time than the best of the single dimension location times. All other combinations give a slightly slower time than the individual dimensions. Color was the fastest of the single dimensions, however, this time was improved slightly when combined with form.

Table 23. Mean Scores for the 4 Single and 10 Compound Dimensions. (Eriksen, Ref. 116)

Single Dimensions	Obtained Mean	Compounded Dimensions	Obtained Mean
Hue (H)	.678	HF	.652
Form (F)	.753	HB	.754
Brightness (B)	.919	HS	.772
Saturation (S)	.942	FB	.772
		BS	.928
		FS	.929
		HFB	.706
		HFS	.766
		HSB	.776
		FBS	.909

*The means are the mean of the logarithms of location time in seconds.

Cohen and Senders (Ref. 81) conducted an experiment to determine if shape or color coding was more efficient in reducing search time and errors in locating dials on visual displays. Twenty-nine subjects viewed banks of black dials with white pointers on white backgrounds. Each dial was 1.75 inches in diameter and the pointer was 7/8 inch long and each was clearly labeled (0.5 in. high). A 0.5 inch ring around each

dial was used for color or shape coding of the dial. The panels of dials were exposed for 0.4 second (Illumination level and viewing distance not specified).

The results shown in Figure 49 indicate that the color code was more efficacious for locating the dials after the initial learning period (first 8 trials). After five days of testing, one day of non-testing was allowed. The sixth day of testing reveals a sharp increase in response time, with the smallest increase appearing in the color coded group. Relearning was also fastest with the color coded group. The authors conclude that color coding is feasible as a means of decreasing locating time in visual displays.

Green and Anderson (Ref. 147) conducted a study to examine luminous color as a partial redundant search code with color-coded alphabet sizes of two, three, and four colors. Twenty observers viewed a display containing two-digit numbers (in the range from 10 to 69) arranged in a random order in a matrix of 10 rows and 6 columns. The numerals were projected onto a screen located 10 feet from the observers. The projected matrix was 16 3/4 by 12 inches while the numerals were 1 1/8 by 5/8 inch. The numbers were either green (Munsell 5.0GY/6/6) or red (Munsell 2.5 YR/6/10), and were presented on a black background. Three

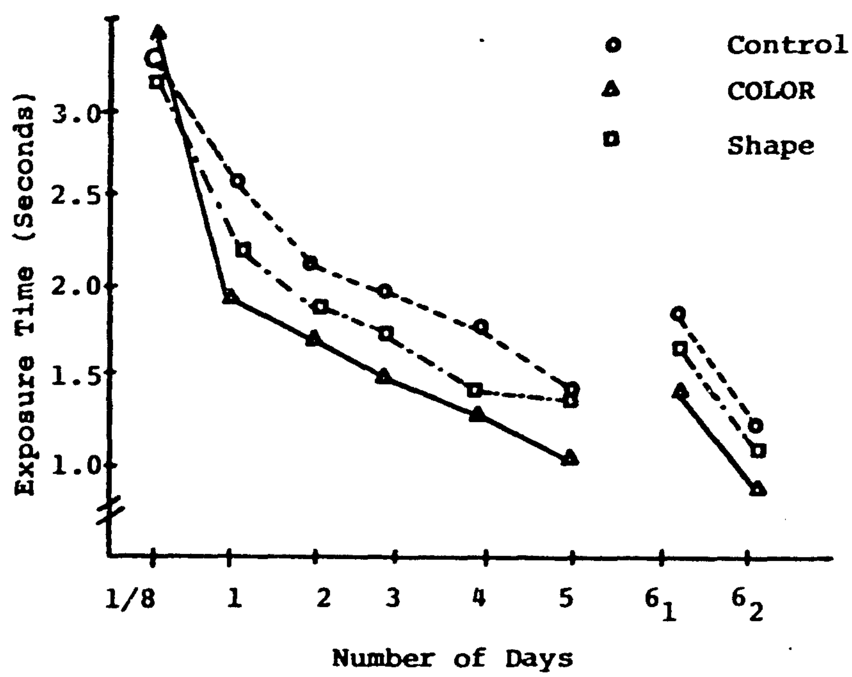


Figure 49. Mean Exposure Time Required by Each Group as a Function of the Number of Days. The Mean for the First Half and the Last Half of Day 6 Trials are Recorded Separately. (After Cohen and Senders, Ref. 81)

experimental conditions were used. In the 'Set' condition, the display contained 60 numbers, of which 0, 10, 20, 30, 40, 50, or 60 were red and the remainder were green. No number appeared more than once in any display so that color was not essential to the search task. In the control condition, the display had 10, 20, 30, 40, 50 or 60 numbers of one color (either red or green) while the remaining positions in the matrix were blank.

The results indicated that when the subject knows the target's color, search time is mainly a function of the number of symbols with the same color as the target (Figure 50). Search times are somewhat longer with multicolored displays than with single colored displays with similar densities. They interpreted these results in terms of Eriksen's hypothesis of display hetrogeneity (even though the number of stimulus categories of a partially redundant code and not the number of dimensions of a totally redundant code was the variable in question). Additionally, since the number of color categories was confounded with display density in this experiment, these effects could possibly be the result of either increments in total clutter or increments in code size.

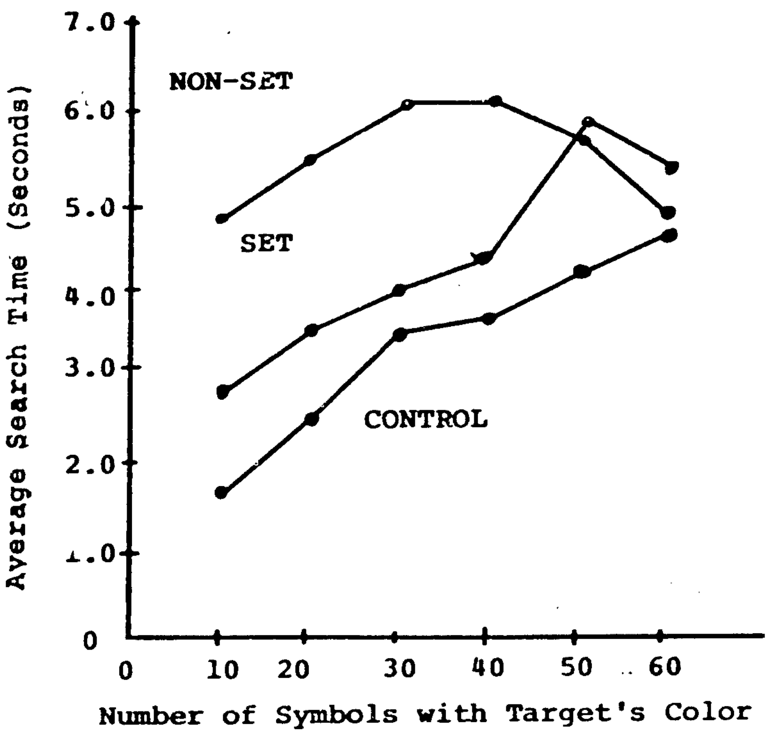


Figure 50. Search Time as a Function of the Number of Symbols With Target's Color. Each Point is the Geometric Mean of 80 Measurements. (After Green and Anderson, Ref. 147)

Anderson and Fitts (Ref. 9) conducted an experiment to determine how much information a subject could report after a tachistoscopic presentation of symbols. The variables used were the information content of the symbols and the method of information coding. Alphabets of nine symbols each were constructed of colored patches, black numerals on white backgrounds, and nine numerals on colored backgrounds. The colors used were: red, orange, yellow, blue, green, violet, flesh, pink and indigo. With the first two alphabets, four message lengths were used: 3, 4, 5, and 6 symbols respectively. The information content varied from 9.51 to 19.02 bits per message. In the colored-numeric alphabet the messages were held to three symbols, with information varying from 6.34 to 19.02 bits per message. The symbols were exposed for 0.1 second to 12 subjects sitting 10 to 12 feet from the screen. There was an alerting signal three seconds prior to exposure of the stimulus. Subjects reported first the color symbol then the number.

The results indicated that performance with color-numeric alphabet was greatly superior to performance with either color or shape alone (see Figure 51). The average amount of information transmitted with three color-numeric symbols was 16.97 bits which was significantly greater than the amount transmitted with six numerals alone (14.30) and the six color patches alone (7.69 bits). Performance with colors was better for messages containing only four symbols than for longer messages (see Table 24). Performance with numbers was slightly better with five symbols than with six symbols.

The results of a second similar experiment with two new subjects tended to confirm the findings of the first experiment. The use of color-numeric symbols led to significantly better performance than did colors or numbers alone.

Alluisi and Muller (Ref. 5) examined verbal and motor responses to several types of codes (color, numeric and inclination), which were presented for short periods of time (0.5 sec.). Their results indicated that performance with the numeral codes was superior in both types of response. Accuracy and speed both were better with numerics, while colors evoked the slowest response and produced the most errors. A combined accuracy-speed measure reflected a task-by-code interaction in which verbal responses were slightly better (in bits/sec) than motor responses for numeral codes, about the same for inclination codes and definitely poorer for color codes.

Conover and Kraft (Ref. 87) conducted an experiment comparing color with shape coding. They concluded that the maximum average information transmission rate for color was 10.44 bits per exposure as compared with 14.94 bits per exposure with numerals while a combination of color and numerals yielded 18.6 bits per exposure.

Table 24. Average Information Gained (in Bits) for Color Alphabet and for Numeric Alphabet. (After Anderson and Fitts, Ref. 9)

Number of Symbols Per Measure	Symbol Position (Left to Right) 1	2	3	4	5	6	Meas. Per Symbol
			Numerals				
3	3.15	3.14	3.14				3.14
4	3.15	3.15	3.14	3.15			3.15
5	3.12	3.08	3.05	2.71	2.81		2.95
6	2.83	2.92	2.84	2.16	1.65	1.92	2.69
			Colors				
3	3.02	2.91	2.82				2.91
4	2.84	2.61	2.30	2.27			2.50
5	2.29	2.04	1.68	1.10	0.90		1.60
6	2.04	1.89	1.44	1.11	0.59	0.52	1.28

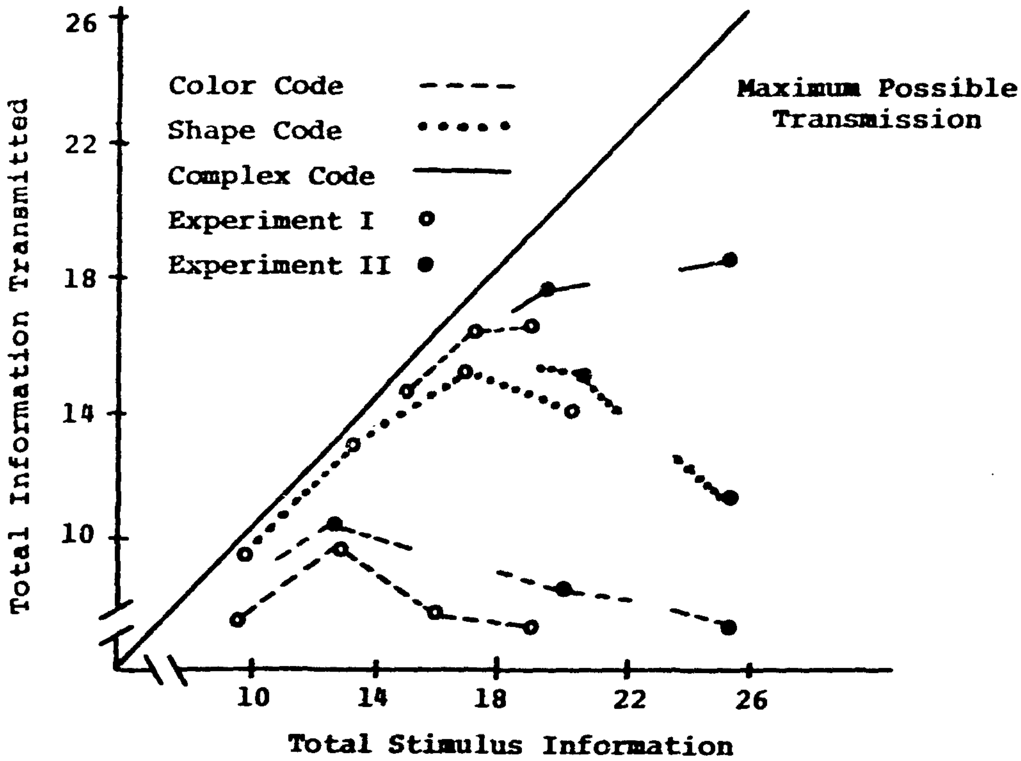


Figure 51. Mean Total Information Gained Per Message. (After Anderson and Fitts, Ref. 9)

It was concluded that the maximum number of hues that could be used for color coding ranges from five to eight. Electronically generated color codes using short persistence phosphors (not specified) permitted only four absolutely discernable hues. The precise number is a function of the viewing conditions and the percentage of the population that must read the code.

Hitt (Ref. 167) made a study to ascertain the relative effectiveness of selected abstract coding methods, based on their effects on various operator tasks. The five codes shown in Figure 52 were selected and the number of code levels were varied over two, four, and eight levels. Target density was also varied over 40, 80, and 120 symbols per display. Five different operator tasks thought to be basic to visual display reading (identifying, locating, comparing, counting, and verifying) were used. The symbols, 1/2 inch for the longest dimension, were mounted in eight columns and five rows on 30 x

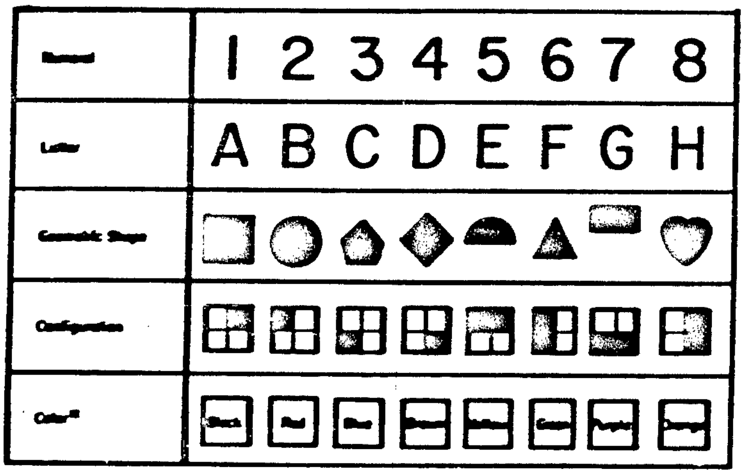


Figure 52. The Five Code Categories Compared by Hitt. (Ref. 167)

*No attempt was made to hold saturation and brightness constant.

22 inch posters. For each of the five code types, nine display posters were made (one code x three densities x three code levels). After initial training to learn meanings associated with each symbol level, the five subjects completed the trials for the 225 experimental conditions at a rate of 15 conditions per session for 15 sessions. The entire procedure was repeated with another set of 5 subjects for cross-validation resulting in a correlation of + .97.

Table 25 indicates that for location, color coding was best. For identification tasks, however, numeral codes were superior with color coding ranking fourth.

As might be expected, increases in both number of code levels and in target density degrades operator performance. The author suggests that numeral coding, or even one of the other coding methods, was superior to color coding if more than nine or ten code levels were desired.

Primisel (Ref. 273) made a further investigation into the amount and nature of the non-target objects with both partially and fully redundant codes. Targets were identified by hue-form combinations amidst varying levels of competing and non-competing clutter. (Competing clutter was of same hue or shape as the target). His findings confirmed the findings of Green and Anderson (Ref. 147) and Smith (Ref. 315). More interesting is the implication in his findings that there is a search-task difference governed by an interaction of the number of competing non-targets with the kinds of non-targets. He found that with small numbers of non-targets that competed in shape or hue, search area seemed to be determined by both dimensions

Table 25. Rank Order of Code Categories as a Function of Type of Task. (After Hitt, Ref. 167)

Tasks	First	Second	Third	Fourth	Fifth
Identify	Numeral 13.64	Letter 13.02	Shape 12.53	Color 12.34	Configuration 11.77
Locate	Color 8.46	Numeral 7.42	Letter 7.25	Shape 6.94	Configuration 4.03
Count	Numeral 12.60	Color 12.22	Shape 11.49	Letter 11.11	Configuration 7.07
Compare	Numeral 6.85	Color 6.72	Shape 6.56	Letter 6.33	Configuration 4.76
Verify	Numeral 10.01	Color 9.95	Shape 9.50	Letter 9.05	Configuration 6.60

Note:

(1) Scores reported in terms of mean correct response per minute.

(2) Code categories connected by line are not significantly different at p = 0.05.

but that with large numbers of competing non-targets the subject's search area seemed to be determined by only one of these.

Conover and Kraft (Ref. 87) state that colors produced by very small sources (saturated spectral hues or surface colors) will appear different to color normal observers if the size of the color patch is less than 20 minutes of visual angle. This small size, when directly fixated, will result in the observer's confusing blues with blue-greens, mauves and gray-greens with greens, and purples with yellows and browns. (For further explanation of this matter, see section on Color Abberation).

S. L. Smith (Ref. 315) conducted a study based on the premise of Green and Anderson (Ref. 147) that visual search time is a fundamental measure of the potential value of display color coding, but expanded it to include a greater range of display densities, more displayed colors, both light and dark

display backgrounds and different methods of display presentation. Eleven men and one woman with normal color vision made a total of 300 visual searches on various display backgrounds. The displays consisted of varying combinations of three digit numbers randomly placed in a square field 12 x 12 inches and viewed at a distance of 18 inches. The displays were made up as 2 x 2 color slides and rear-projected producing symbols on the screen of 1/3-inch high by 1/6 inch wide. The colors used are listed in Table 26. Ambient illumination was over one-half foot candle. The experimenter indicated the target digit and color (or noted that color was "unknown") on a separate display and then exposed the slide. The subject searched for the target and when found it pressed one of 10 buttons corresponding to the third digit in the series.

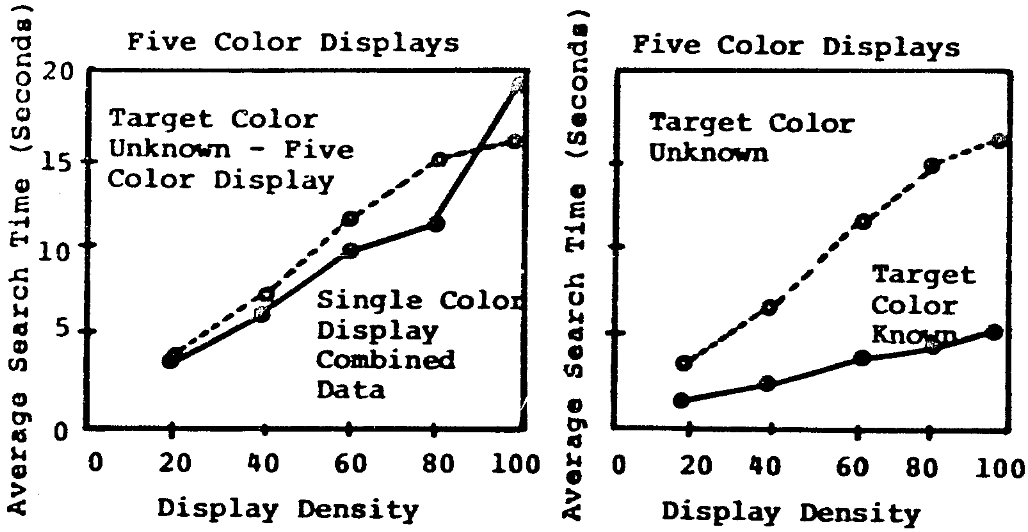
Table 26. Colors Used by Smith (Ref. 315)

Display Color	White Background (Munsell Notation)	Black Background (Munsell Notation)
Red	2.5 R 5/10	5 R 5/12
Green	7.5 GY 8/8	5 GY 7/8
Blue	2.5 PB 6/8	2.5 PB 6/8
Orange	2.5 YR 7/10	2.5 YR 7/10
Black/White	7.5 P 3/4	N 9/0

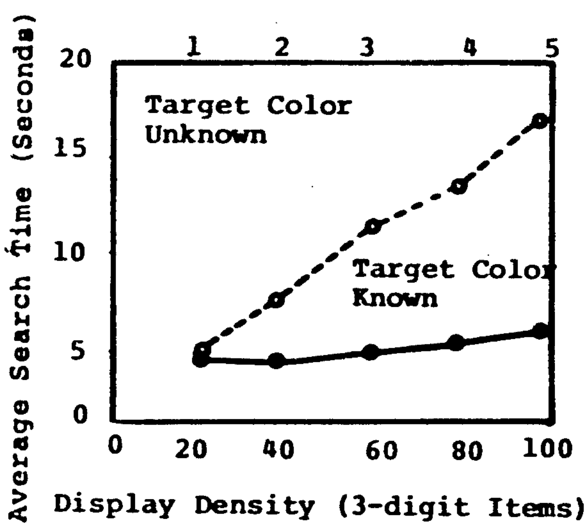
Neither the particular color of the target number, nor whether the display had a dark or light background, nor the interaction of these factors had a significant effect on visual search time. Other conditions being comparable, average search time increased steadily with increasing display density. (Figure 51). On the multi-colored displays, when the color of the target number was known in advance, average search time was considerably shorter than when the target color was unknown. When the color of the target number was unknown, a comparison of search time on single-colored versus multi-colored displays showed no significant difference (Figure 53-a).

The authors apparently found no evidence of field heterogeneity effects on search time under non-set conditions (color unknown). With a color-set condition, he did find a slight effect attributable to wrong-colored items.

Jones (Ref. 186) remarks that one thing is apparent from both of the above studies: that search time is decreased by the concomitant use of a partially redundant color code as a code set. Furthermore, the decrease is proportional to the number of colors used with a given level of density.



a. Single vs Multicolor Display b. Known vs Unknown Target



c. Known vs Unknown Target
(Varying Number of Colors).

Figure 53. Search Time as a Function of Display Density and Target Identity. (After Smith, Ref. 315)

Smith and Thomas (Ref. 317) attempted to measure systematically the apparent superiority of display color coding by comparing it with various shape codes in the context of a relatively simple operator task, that of counting a particular class of displayed items. Forty-five slides were used, each containing 20, 60, or 100 symbols (bright colored figures on a dark background) to produce a 29-inch square display field viewed by eight subjects seated approximately five feet from the screen (see Figure 54). Ambient illumination was about two foot-candles. Some displays were multi-colored (each symbol could appear in any of five colors) while in other displays all symbols were of the same color. Subjects counted each of these displays 10 times, once for every shape and once for every color.

A second set of 15 100-item slides were used to examine the effectiveness of shape-coding while color did not vary. A third set of five multi-colored displays, on which one military symbol appeared 100 times, represented in all the various colors, was used to study the effects of color on shape counting.

Inspection of Figure 55 indicates that colors were counted about twice as fast as the best set of symbols and three times as fast as the poorest symbols code. Fewer errors were made with

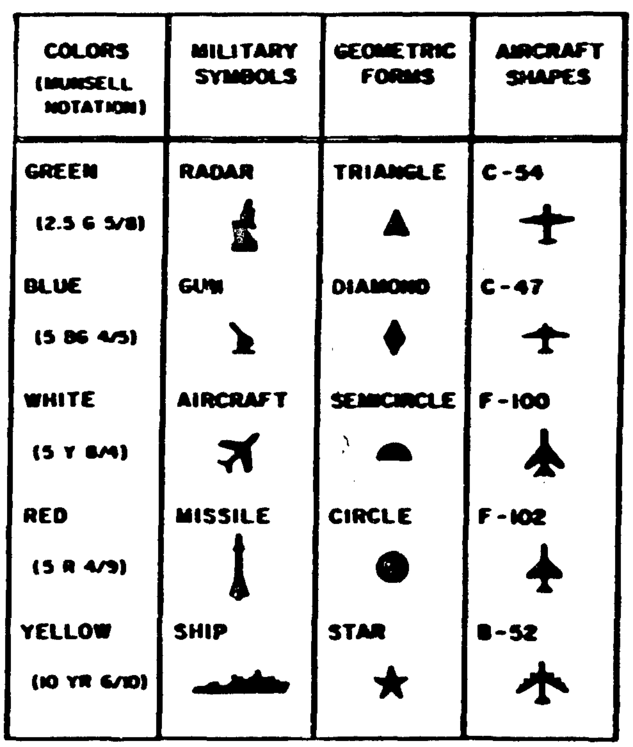


Figure 54. Colors and Symbols Used by Smith et al. (Ref. 317)

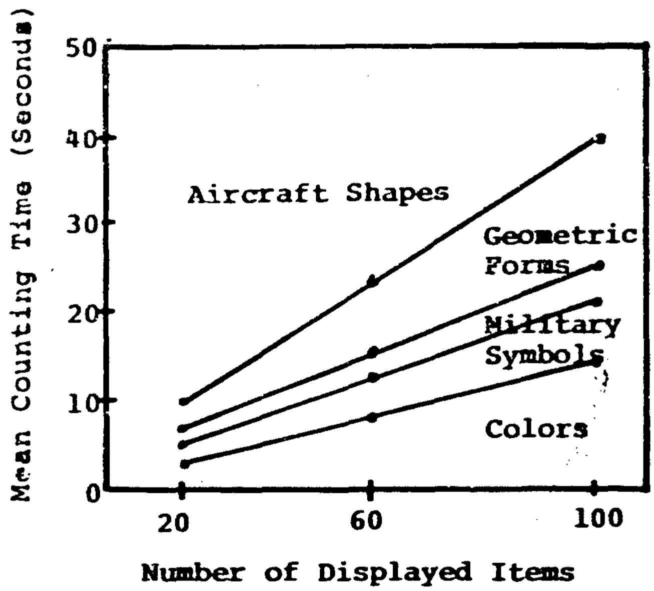


Figure 55. Average Counting Time for Color Coding and Three Shape Codes as a Function of Display Density. (After Smith and Thomas, Ref. 317)

color counting than with shape counting and fewer errors were made at low display densities than at high densities. Statistically reliable differences in counting time were confirmed ($p < .001$) attributable to display density, the particular shape code displayed, the code used for counting (shape or color) and all interactions of these variables. There was no noticable effect on color counting attributable to the shape code on which color was superimposed. However, a statistically reliable difference ($p < .01$) was attributable to various shapes in shape counting. Additionally, there was apparent improvement in speed and accuracy of shape counting when variable color was eliminated from the display. The average counting time for the military symbols and for the geometric symbols was comparable with a slight advantage to military symbols. Counting time for aircraft shapes was substantially higher than for military symbols or geometric forms, respectively.

Summary

It is evident that the application of color as a coding dimension enhances performance in visual search tasks. Combining the color code with other forms of coding (alphanumerics and shape coding) also aids in performance up to a point. The added dimensionality of color also increases the information rate that can be presented in a given display. These favorable results,

however, are tempered by the fact that most of these results were obtained under low and steady light levels. The effects of rapidly changing illumination has not been explored. Additionally, the effects of high ambient illumination upon color coding requires examination.

A final significant factor is the fact that none of the studies examined addressed the problem of color coding on colored CRT type displays. The interaction effect of electronic display phosphors (for colored displays) and changing illumination conditions may produce significantly different results. This area will require careful examination.

DISADVANTAGES OF COLOR CODING

Conover and Kraft (Ref. 87) reviewed some of the problems associated with color coding and compiled the following list of general disadvantages associated with color:

1. The average color-normal person can discriminate only about nine hues of surface color on an absolute basis under ideal conditions, and even fewer under adverse conditions.

2. Some people are color-defective; about 8% of all males and 0.4% of all females.

3. Color discrimination is seriously degraded when surface colors are viewed under highly chromatic light sources.

4. Even with recent improvement of colored phosphors for use on CRT type displays, the presentation of satisfactory colored symbols by electronic means in video displays still presents technical problems.

5. Character and stability of the display environment is difficult to create and control. Color judgements are influenced by many aspects of the surrounding conditions. Homogenity of background, color and intensity of adjacent areas, differences between expected and actual conditions of illumination, perceived location of color relative to its surround, and the visual impressions that colors are abstract or attached to an object are examples of these factors.

6. All color coding methods present practical problems in maintenance. Surface colors have a tendency to fade with age. Signal lenses may crack or become obscured by dirt. Electronically generated color symbols are subject to distortion and (color) noise bursts and to effects of aging phosphors.

7. Signals or color patches of small dimensions, 20 minutes or less in visual angle, cause normal subjects to show certain characteristics of anomalous color vision. Color codes

recommended for two degrees or larger do not apply to 20 minutes or smaller sources of light.

In addition to these general limitations, a number of specific disadvantages have been uncovered in the literature. Snadowsky et al. (Ref. 318) for example, discussed the problem of misregistration of color on symbology. He defined registration as the superimposition of a homomorphic image to form a composite single image. Misregistration, then, is the degree or percent of misalignment of these images and is defined as:

$$\text{MISREGISTRATION} = \frac{M - S}{S} \times 100\%$$

where M = the strokewidth of the misregistered image and
S = the strokewidth of the perfectly registered mixture character and the unregistered primary color character.

By this definition, then, an image with 0% misregistration is completely aligned while an image with 100% misregistration represents two distinct images precisely adjacent to each other. Based on the results of his experimentation, he recommended that misregistration cannot exceed 33% under operational conditions without loss of performance. Fifty plus percent misregistration results in serious performance loss. This recommendation required validation, however, since it applies only to normal operating conditions and not to adverse operating conditions. Combined with the other variables found in a "worse case" viewing situation, the misregistration tolerance may be found to be considerably lower than 33%.

Another specific disadvantage with the use of color is the problem of chromatic aberration. (Chromatic aberration is discussed in more detail in Section III.) Back in 1949, Duke-Elder (Ref. 108) discussed the fact that the eye functions in some respects similar to a prism in that both refract light. In both the lens and the prism, shorter wavelength light is bent to a greater extent than longer wavelength light. This degree of refraction (or bending) is related in inverse proportion to the wavelength. Myers (Ref. 253) suggests that because of this characteristic, only one wavelength can be focused on the retina at a time. For example, when yellow-green rays are focused on the retina, blue and red rays should be both equally unclear with their focal points falling to the front and the rear of the focal plane, respectively. This effect is referred to by Duke-Elder as "Chromatic Aberration".

Jones (Ref. 186) notes that the problem of chromatic aberration is of critical concern because of its effect on visual acuity. She suggests that either the use of a small

colored stimuli or moderately sized stimuli viewed at a distance would be inadvisable for reliable color coding.

Mitchell and Mitchell (Ref. 242) have referred to this aberration effect as "Chromatic Myopia". In their study it was found that under blue light, distant objects (6 feet or more) are imaged in front of the retina and the normal emmetropic eye is not able to adjust to the differences, since it's accommodative power is already at it's maximum.

In a study to more clearly define this problem, Myers (Ref. 253) conducted a study to ascertain possible adverse accommodation effects which might result in the loss of visual acuity in color coding. Five males, ages 21 to 32, served as subjects, each having 20/20 vision and normal color vision. Two 35 mm slide projectors were used; one to project the Landolt C-ring image (see Figure 56) (either red or blue) and the second to project the colored (red and blue) area surrounding the rings. Eight different size C-rings were used for each subject for each color combination. (See Table 27)

The response unit consisted of four pushbuttons in positions corresponding to the C-ring opening positions (3, 6, 9, 12 o'clock). The S determined the location of the opening and depressed the appropriate button. A total of 140 presentations were prese ted for each stimulus-surround color combination. Subjects sat in a chair in a darkened room with their chins in a rest 28 inches from the screen. The image was exposed for 0.75 second and the subjects were instructed to "guess" even if they were not sure of the location.

The results supported the general hypothesis that the red stimulus condition would result in better performance than the blue stimulus. The order of performance resulted in the R/R (red stimulus/red background) condition having the smallest aperture size threshold, followed by the B/B (blue stimulus/blue background) and R/B (red stimulus/blue background), respectively.

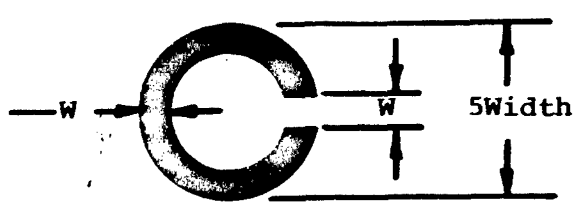


Figure 56. The Standard Landolt "C" Ring,

Table 27. Sizes of C-Ring Apertures in Inches and in Min. of Arc and Seconds of Visual Angle. (Myers, Ref. 253)

	Size on Slide (Inches)	Size Projected on Screen at 70 Inches (Inches)	Visual Angle at 28 Inches.
1.	.0019	.0131	1', 37" or 1.62'
2.	.0023	.0158	1', 56" or 1.93'
3.	.0027	.0186	2', 16" or 2.27'
4.	.0031	.0210	2', 35" or 2.58'
5.	.0035	.0236	2', 54" or 2.90'
6.	.0039	.0263	3', 14" or 3.23'
7.	.0043	.0290	3', 33" or 3.55'
8.	.0046	.0316	3', 54" or 3.90'

(See Table 28). The average percent of correct reponse for each of the four conditions were:

Table 28. Summary of Results, (After Myers, Ref. 253)

80.1%	Red Stimulus/Red Background
73.5%	Blue Stimulus/Blue Background
60.5%	Red Stimulus/Blue Background
50.4%	Blue Stimulus/Red Backgroun

Figure 57 indicates a general decrement in performance with the blue stimulus for the range of aperture sizes used. On the other hand, the fact that the threshold for both red stimulus conditions was higher than those for the blue stimulus conditions indicates that the size factor was consequential in determining overall color difference.

Myers concluded that the "critical" size to which color may be applied to a visual display varies with the particular situation and with the colors employed. The results of his study do not appear to support Conover and Kraft's recommendation of a general 20 degree visual angle cut-off point. In fact, Myers concluded that in most applications, the small differences in visual acuity resulting from accommodation differences with various color combinations would not be a serious impediment to

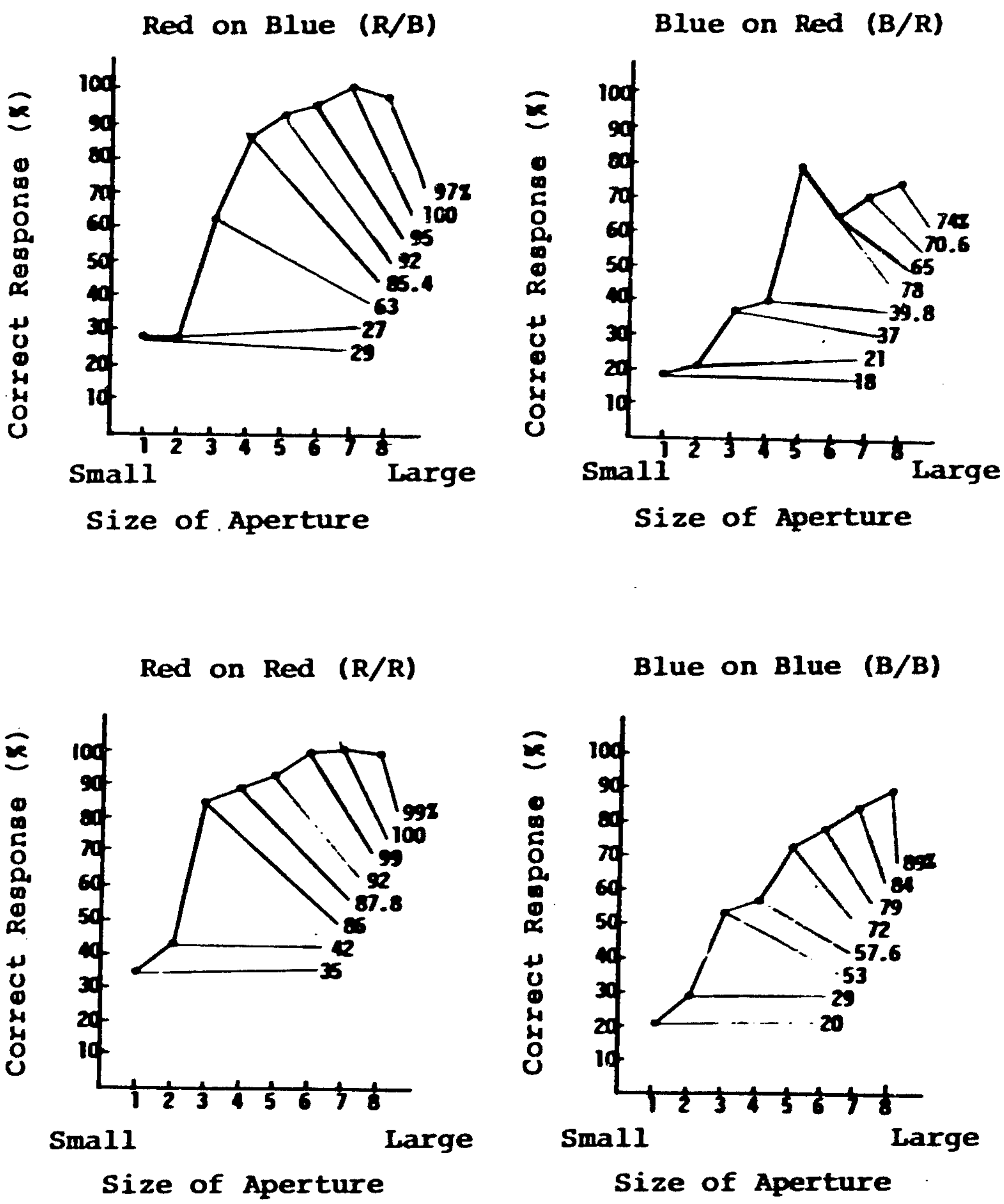


Figure 57. Mean Correct Response for all Subjects for Each Stimulus Level and Each Condition. (After Myers, Ref. 253)

the use of color. Blue would be the exception, since the eye focuses this color myoptically. In any case, the loss of visual acuity was only critical with small degrees at a visual angle of less than four minutes.

CONCLUSIONS AND RECOMMENDATIONS

With the already present partially redundant coding dimensions present on most displays (position coding, size coding, shape coding, etc.), one must seriously question the need for the addition of color coding to airborne displays. The advantages derived from its use would have to be greater than the current literature indicates. The demonstrated utility of color codes is maximal in large, complex, cluttered and unstructured displays. The opposite is true of most airborne displays; simplicity, compactness and well-defined structure are basic factors in their design.

It is admitted that the addition of color to airborne displays may serve to improve pilot acceptance factors, but the cost of so doing is great. Careful research is needed to relate color-coding in electronic flight displays to the many human performance variables and environmental variables in realistic operational type tasks. Any such research should take into consideration the many environmental factors associated with airborne electronic displays: ambient illumination levels, vibration, the interaction effect of other light emitting sources within the cockpit, the various stress levels the pilots situationally experience, and many more. In the case of head-up displays, the added factors of buzzing, real-world backgrounds are added to the list. All of these factors require careful examination with respect to the use of color coding.

One starting point from which to make the above decision is to establish the performance requirements of the display observer. What is it exactly that the observer must do and what information is required for him to accomplish this task? When information requirements have been established, the optimum presentation formats for the information can be addressed. The format examination should include the efficiency of the dimension (in terms of human as well as equipment performance and reliability), the reliability of the dimension (performance under normal as well as adverse viewing conditions) and the cost of the dimension (in terms of research required, training and equipment).

When the above evaluation has been completed and color coding of the information appears to be warranted, the literature provides an indication as to which colors would be likely candidates for further evaluation. Hues in the yellow-green and red range of the color spectrum appear to offer the most

promise. However, evaluation under the proposed operating conditions is mandatory. No data, for example, have been found in the literature addressing color discrimination under high ambient illumination conditions (over 1,000 ft. Lamberts). (However, reports have been made of colored aeronautical chart symbols 'disappearing' under daylight flight conditions because the colors were 'washed-out' - Eriksen, Ref. 371).

Representative design variables that should be examined in the evaluation of different hues for use on electronically generated displays would include:

High Intensity Ambient Illumination - What effect does high intensity ambient illumination (1,000 to 8,000 plus ft. Lamberts) have on color discrimination? What hues are equally discriminable under these viewing conditions and what are the effects of different observer visual (locating, identifying, etc.) and motor tasks (tracking, adjusting) on discrimination?

Chromatic Visual Environment - How do changes in the visual environment chromicity affect color discrimination (i.e., viewing under sun-up or sun-down conditions)? What is th ıaximum size of the color alphabet (100% discriminable) obtain..le under these viewing conditions?

Glare Factors - What are the effects of glare on color discrimination under high ambient (and chromatic) viewing conditions? What interaction effect is encountered (if any) with the introduction of filters and visors in the glare environment?

Color Contrast - What are the contrast requirements for color discrimination under high ambient illumination (up to 8,000 ft. Lamberts) viewing? What is the optimum background brightness for comfortable viewing under the above conditions? (Contrasts of 25 to 100% should be examined with an emitted display background luminance of about 180 ft. Lamberts).

Symbol Size and Shape - What is the optimum symbol size (including stroke width and stroke-width-to-height) and shape for the color code under the above illumination conditions? Simple solid geometric forms should be evaluated with sizes ranging from two to three minutes of arc and up. One hundred percent discriminability thresholds should be established as a function of different shape-color combinations.

As with any other visual performance measure pertinent to electronic displays, the observer performance measure should be a minimum of 100% legibility under all anticipated viewing conditions. Additionally, the minimum should optimize reading time, detection time or identification time, depending upon the visual task to be performed. Subjective observer preferences should be included in the above evaluation, where possible.

FLASH RATE CODING

Introduction

There appears to be little in the way of data relating to flash rate coding. The few data that are available tend to shy away from recommending this method of coding if other methods are available. There are, however, some new and encouraging possibilities for the use of this dimension.

An early review by Gebhard (Ref. 128) indicated that flash rate coding was a possible but not very practical means of representing information. He suggested the use of a course flicker which stayed well below the fusion frequency. The frequencies he suggested for scaling into a usable code ranged from about 0.5 to 30 flashes per second with the retinal intensities about 10 millilamberts for the 30 flashes per second rate. He found about 15 discriminable steps between 0.5 to 30 flashes per second, but reliability was poor. The author suggested that it would be more profitable to use simpler on-off type flash codes.

Gerathewohl (Ref. 132) conducted a series of studies on flashing light signals. He found that flashing light signals were more conspicuous than steady ones when brightness contrast is low.

Gerathewohl (Ref. 135) investigated how conspicuous flashing light signals are at three different flash frequencies and duration rates (1, 2, and 4 flashes per second and durations of 1/2, 1/4, and 1/8 second each). The results indicated that when the subject had a complex psychomotor task, the flashing light's efficacy as a warning depended on the conspicuity of a series of flashes, not on the luminance of a single flash alone. With a luminance of 1 millilambert, subjects will respond to a series of light flashes in a complex situation with the same speed regardless of whether the flash is once each second, or four times each second with a 1/8th of a second flash duration. At low contrast, the short, fast flashing light appeared to be more conspicuous than the longer, slow flashing light. Gerathewohl concluded that subjects responded more quickly when the flash rate was faster. Three flashes per second was the fastest rate he used in this particular study.

Baker and Grether (Ref. 12) found little in the way of data applying to flash rate coding. They determined that five flash codes could be discriminated under ideal conditions. However, they found this dimension unsatisfactory because high brightness is required if a high flicker rate is to be seen as flicker. They indicated also that this coding dimension is annoying to the operator.

Cohen and Dinnerstein (Ref. 80) conducted a study to examine the relationship between flash frequencies and the ability to identify various flash rate frequencies correctly. They used 10 subjects to judge nine flash rates that varied from one flash each four seconds to 12 flashes per second. The stimulus used was a high intensity blue-white Strobotron tube, masked to a point source.

The results indicated that their subjects could discriminate an absolute maximum of five flash categories under the best conditions. Even with only four stimulus categories, occasional confusion occurred. The authors recommended using only three flash rates for an operational situation:

4 flashes per second

1 flash per second

20 flashes per minute.

Morgan et al. (Ref. 247) recommends that flash rates be limited to no more than four rates and that these should be limited to only one or two items on the display itself.

Honigfeld (Ref. 171) reviewed the literature and concluded that flash rate is a poor way to present information. She found it detremental to performance under all conditions as it is critically influenced by brightness and size. With high flicker rate, the target must have high brightness and large size. Flickering light, especially at certain rates, is annoying to view.

She did conclude, however, that under certain conditions, one could make good use of the annoying properties of this code. The periphery of the eye is especially sensitive to intermittent stimulation between two and sixty cycles per second. These frequencies are recommended only to attract attention. This flicker range may also produce apparent movement, which may or may not be beneficial. Honigfeld recommends Cohen and Dinnerstein's suggested rates for coding: 4 flashes per second, one flash per second and 20 flashes per minute.

Ziegler, Reilly and Chernikoff (Ref. 365) conducted two experiments to (1) determine the effects of adding flash coded directional information to a conventional displacement display and (2) to compare a display system which indicates error direction by means of flash coding with one where flash coding of error direction is combined with brightness coding of error magnitude (the latter being referred to as "depth-of-flash" coding).

The display used in Experiment I was a five inch CRT tube with a 1/2 inch long horizontal reference line centered on the tube and a 1/32-inch diameter dot moving along the Y-axis normal to the center of the reference line. The dot flashed on and off with a 50-50 duty cycle. When the dot was 1/8-inch or more above the reference line, it flashed at a rate of 60 cpm to indicate high error direction. When the dot was 1/8 inch below the reference line, the flash rate was 120 cpm, providing "low" error direction information. No flashing occurred if the dot was within the ± 1/8-inch range of the reference line. Each display was tracked at a viewing distance such that the maximum visible dot displacement, from the reference line, subtended visual angles of 1, 2, 4, 8, and 16 min at the eye of the observer. Each of seven subjects served in three sessions on each of the five visual angles. The subjects were dark adapted for 15 min. prior to each session.

The results of Experiment I are summarized in Figure 58. As visual angle decreased, tracking error was found to increase for both the displacement-coded and displacement-plus-flash-coded displays. At certain angles, performance was improved by the addition of flash-coded error information.

In Experiment II, eight different dark-adapted subjects viewed the display from a sitting position 16 feet from the CRT tube. A 1/16-inch diameter spot of white light was flashed in a similar manner to Exp. I but the brightness of the light varied as a function of the amount of error (between 50 and 1200 Ft-L).

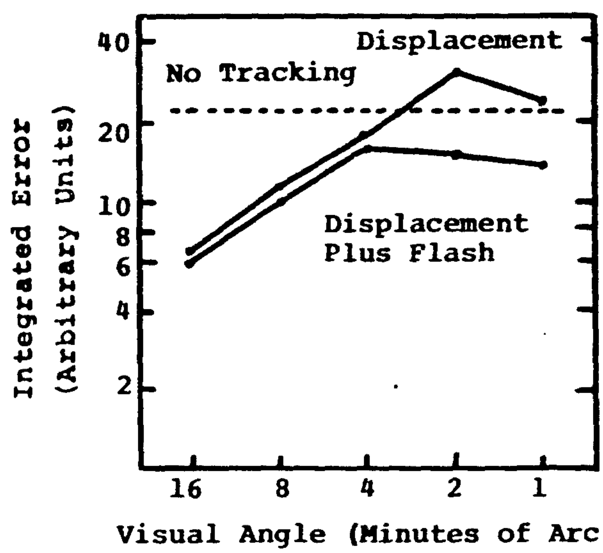


Figure 58. Tracking Error as a Function of Visual Angle for Experiment II. (After Ziegler et al., Ref. 365)

As the error decreased, the brightness difference above and below the reference brightness became less until at zero-error the subject momentarily saw a steady light of 600 Ft L. The average brightness of the display remained constant (but unspecified).

The results are summarized in Figure 59. The authors found the difference between the displays to be significant with the flash coded display superior in all but the first two sessions.

After the initial sessions approximately 1-1/2 times as much error was made when display information was limited to error direction alone. The superiority of the depth-of-flash was evident after a relatively short learning period.

The last study indicates some of the possibilities for flash rate coding of information. It is also evident that much careful work is needed in this area before this technique can be perfected.

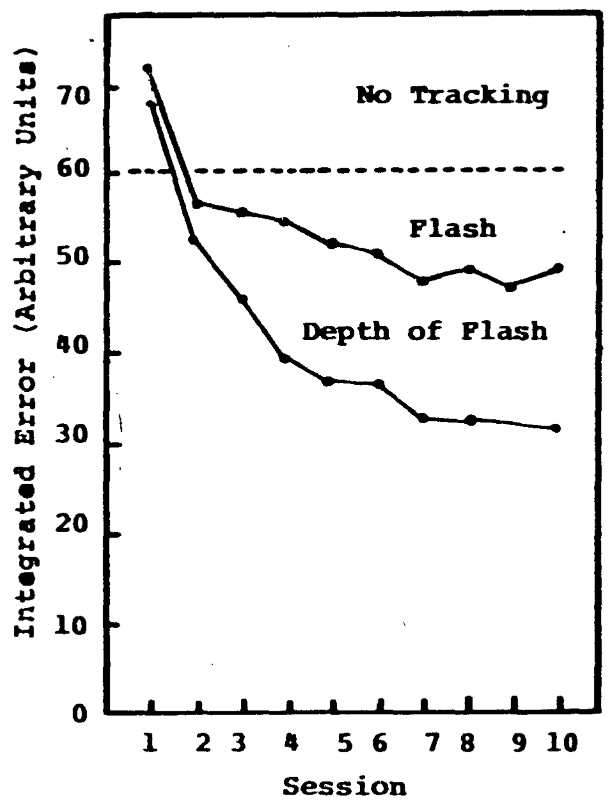


Figure 59. Tracking Errors as a Function of Training for Experiment II Coding Methods. (After Ziegler et al., Ref. 365)

Summary

The majority of the literature reviewed here tends to fall into one of three categories:

1. Flash rate coding is the least desirable of the several dimensions of coding available for visual displays. As such, it should only be incorporated into the display as a "last resort".

2. That flash rate coding is useful*, but limited in scope, with three to five distinct, discriminable flash rates available. In this category, Gerathewohl suggests flash rates of 1, 2, and 4 flashes per second with durations of 1/2, 1/4 and 1/8 second each.

3. That the full potential of flash rate coding has not been exposed. In this group, Ziegler et al. have shown that flash rate and depth-of-flash coding do offer possibilities for unique encoding of information. More research and validation remains to be done in this area, but it does appear to offer possible new approaches to the coding problem.

*There appears to be little question as to the value of a flashing light as an attention-gaining device. (Gerathewohl, 1953, Baker and Grether, 1954, Honigfeld, 1964). However, the fact may be often overlooked that this too is a coding dimension.

SECTION V

ALPHANUMERIC DESIGN CONSIDERATIONS

INTRODUCTION

> Ketchel and Jenney (Ref. 206) recently state, "Of all the coding techniques, alphanumerics has attracted the greatest attention because letters and numerals offer almost limitless possibilities for encoding information. The optimum characteristics of alphanumeric codes for various applications have been the subject of intense investigation over the years, and nearly half of the research reports ever published on symbology deal with some aspect of alphanumerics".

This section reviews the research dealing with pertinent factors in the legibility of numerals and capital letters, and the development of legibility recommendations for alphanumeric symbols to be used in operational electronic display systems.

It is not the purpose of this section to review the entire body of research relating to alphanumerics, but rather to present research material directly supporting alphanumeric legibility recommendations for cathode ray tube (CRT) displays and near related electronic displays.

Specifically, the literature was reviewed with the objective of presenting design-oriented guideline data on the following legibility features of alphanumerics for electronic display application:

- Font or Style
- Symbol Size and Proportion
- Symbol Spacing
- Words
- Edge (off center of tube) Displayed Symbology
- Viewing Angle
- Symbol Blur
- Matrix Symbol Generation Techniques

These physical factors were manipulated as independent variables for the studies reviewed. For these variables it was necessary to establish meaningful performance measures, or dependent variables, which would specify acceptable operator performance criteria and validly reflect display system performance.

The dependent variables selected for this task were chosen based upon the following criteria. First, consideration was given to the performance measures which define symbol legibility:

accuracy, rate, speed, and threshold of identification. Second, it was necessary to establish which measures had been used in alphanumeric research concerned with symbol legibility and third, careful consideration was given to those measures of legibility which reflect the performance required of a pilot in an operational cockpit setting.

Because research was available on all the performance measures defining symbol legibility, reasons one and two did not eliminate any dependent measures from consideration. The pilot's operational setting did, however, eliminate threshold of identification since it was considered inapplicable as an operational measure of legibility. This was because (1) threshold of identification is usually determined by measuring the distance from the eye to the symbol when the number of identifications are either 50 percent correct (50 percent threshold) or 100 percent correct (100 percent threshold) (Ref. 303), and (2) only a 100 percent correct level of identification is acceptable for systems usage. This eliminated from consideration all studies with a 50 percent correct level of symbol identification. Those studies with a 100 percent correct threshold were included, provided the viewing distances used were close to the 28 inch operational standard. In such cases, these studies were considered under "accuracy of identification".

As mentioned, prime consideration was given to those performance measures which best describe the pilot's legibility requirements. These are whether or not the pilot can accurately identify the symbols, and the speed or rate at which he can identify them. It should be noted that, since speed of symbol identification is measured as the time in seconds from symbol presentation to symbol identification, it applied only to those studies which did not use a fixed exposure time.

Having established that accuracy and speed or rate of symbol identification are acceptable as dependent measures of alphanumeric legibility, it remained to specify the acceptable operator performance levels for each of these measures. As an examination of the variety and complexity of any electronic flight display task will reveal, it is difficult to specify a generally acceptable systems performance level for speed or rate of symbol identification without carefully examining the individual requirements of the given task within the framework of the overall aircraft system. This suggests that speed or rate information taken from reviewed studies and intended for design purposes be carefully evaluated against operational requirements. If operational requirements are not available, then these data should be used as guidelines for projected "worst case" design considerations. When considering accuracy of symbol identification, however, a performance level approaching 100 percent correct identification is generally necessary for acceptable systems usage. This is a requirement consistent with

the operational philosophy that says an operator may be allowed considerable tolerance, for a variety of circumstances, in the absolute time (rate) permitted to identify a given symbol and still be effective, but that his identifications must, in all cases, be accurate to be useful in the system.

Having established the desirable independent variables and what constitutes an acceptable dependent performance measure, it remained to find alphanumeric legibility studies consistent with these requirements.

Ideally, exact alphanumeric legibility recommendations could be generated from the existing literature for each condition effecting the operational use of CRT's in flight displays. In reality, however, the body of research currently available is not adequate to this task. Shurtleff (Ref. 304), a recognized authority on alphanumerics, conducted a three-year comprehensive study to establish alphanumeric legibility specifications for visual display devices, and concluded that "the data are not complete enough, nor described in sufficient detail, for one to be able to specify unequivocally what the values of each relevant factor should be for a given display situation."

In addition to the incomplete data found in the literature, certain methodological problems limit the utility of those data which are available. One of the more confounding of these problems is the use of extremely short exposure times frequently used for presenting symbology. Studies which employ an extremely short viewing time are generally attempting to challenge the capabilities of the subject in order to introduce errors which can be analyzed and compared statistically, the idea being that an alphanumeric configuration which performs well under these limited viewing times will also perform better under operational conditions. This has not always been found to be true. For example, in the area of linear scales (Refs. 66 and 67), reading accuracy for one scale was found to be superior to a second scale when both were tested at .075, .15 and .3 seconds, but when these same scales were tested at .6 and 1.2 seconds, the latter was found to be better. Moreover, in terms of flight display, Gainer and Obermayer (Ref. 125) have found that from .3 to .7 seconds is a typical range of eye fixation times for a variety of instruments. Within the studies reviewed in this chapter, care should be exercised in extrapolating from data where the exposure times are much less than .3 seconds.

A second methodological problem encountered in the literature has been reduction of symbol brightness, which, again, is usually done to obtain a more workable distribution of scores for statistical analysis. This means that for studies where the subjects view symbology under low lighting conditions, interpretation of the results must take into consideration whether or not those characteristics which seemed to improve legibility are effective for dim illumination conditions only. The necessity

for this precaution is demonstrated in a study by Brown and Lowery (Ref. 45) where variations in stroke width to height were found to improve legibility for poor brightness conditions, but had no effect on legibility when symbol luminance was increased.

Realizing that there are limitations within the existing literature dealing with alphanumeric legibility, it seemed appropriate to establish the following hierarchy of study presentation. Only those studies concerned with the objective evaluation of numeral or capital letter symbol legibility, under controlled and specified experimental conditions by visually screened subjects, were considered for this review. Exception to these criteria were permitted where particular study results appeared to contribute to an area void of technically acceptable research. Where such studies were used, mention is made of their inherent limitations and any conclusions drawn from them are qualified. These requirements naturally eliminated much research from inclusion in this review. However, for those interested in a general summary on alphanumerics, Cornog and Rose (Ref. 90) have published an excellent reference handbook encompassing over 200 studies.

Likewise, studies pertaining directly to electronic display devices were given priority consideration. Where electronic display research was missing, or sketchy, supplemental non-electronic display material was used if it was available. If research voids existed in an area, the opinions expressed by recognized authorities may be cited, or the authors' opinions, based on the total body of literature reviewed may be presented. Finally, recommendations are given for future research designed to eliminate existing data voids.

FONT OR STYLE

Introduction

As applied to display systems design and usage, font refers to the fundamental geometry or style of a particular set of alphanumerics. It is the basic framework for the generation of a set of alphanumerics and, therefore, effects other symbol characteristics such as width-to-height and stroke-width-to-height.

The font of letters and numbers used in displays is especially relevant to human factors considerations of legibility, an element in alphanumerics that has been variously defined. For example, McCormick (Ref. 230) defines legibility as "the attribute of being able to identify given letters or numerals to the exclusion of others and depends primarily on such features as stroke width, form of character, background, size and illumination".

For this review, however, legibility is defined as a property of alphanumerics which is measured in terms of three objective performance criteria: accuracy, speed, and rate of symbol identification. The following section reviews research that relates to changes in legibility resulting from the use of varying alphanumeric fonts.

Because so little useful research has been conducted on alphanumeric font using operational electronic displays, the following section on font comparisons for non-electronic visual display devices is presented as supplementary information. While the experimental conditions surrounding each of these supplementary studies qualify them according to the selection criteria for inclusion in this review, details of the research are not presented, both for the sake of brevity and because these conditions were not judged to be directly applicable to electronic display usage. For a complete description of the experimental conditions, see the specific studies cited, and for an excellent in-depth summary on non-electronic display devices, see Shurtleff (Ref. 303).

Non-Electronic Display Studies

Mackworth (Ref. 229), in his original attempt to improve the legibility of a complete set of alphanumerics, developed the Mackworth style (see Figure 60) which he evaluated against letters similar to the AND 10400 style (see Figure 61) and numbers similar to the Leroy style (see Figure 62). Presenting the symbols individually for 1.62 seconds at 10 Ft. Candles of illumination, he found that for accuracy of identification, his font was superior to the AND 10400-Leroy letter-number combination. But as Crook and Baxter (Ref. 93) point out, differences

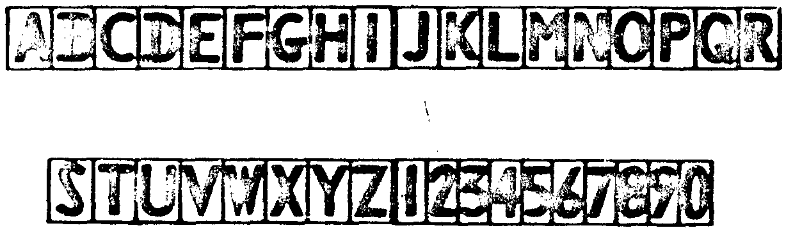


Figure 60. Mackworth Alphanumerics.

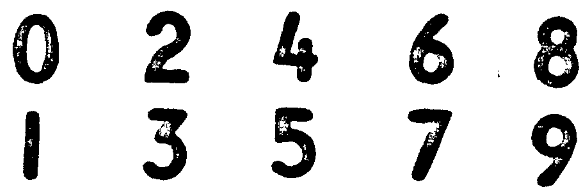


Figure 61. AND 10400 Numerals.

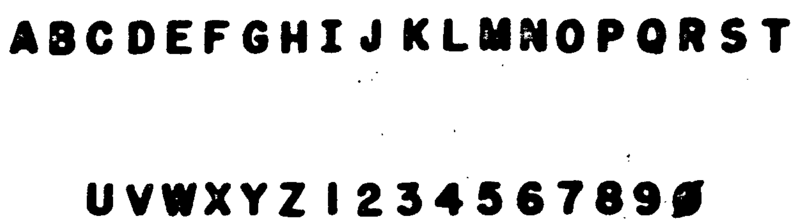


Figure 62. Standard Leroy Alphanumerics.

in brightness contrast and overall symbol size may have given the Mackworth style an advantage in the comparison, and this may have confounded the study conclusion of apparent superiority.

The AND 10400 numerals were further compared with Berger numerals (see Figures 61 and 63) by Brown, Lowery and Willis (Ref. 46) with the height, width, and width-to-height percentage held constant. Mean error scores indicated that the only significant differences between the two styles were for the digits "4" and "9". The Berger "4" was significantly better than the AND "4" for two sets of experimental conditions. First, for trans-illuminated brightness levels of 0.33, 0.79, 1.63, 2.60 and 3.34 Ft. Lamberts at 0.20 and 0.04 second viewing times, and second, for a floodlight condition where illumination brightness levels of 80 and 40 Ft. Candles were used with a 0.007 second viewing time. The AND "9" was significantly better than the Berger "9" for the floodlighted condition only. The viewing times of 0.04 and 0.007 seconds are extremely rapid for normal systems application, but the superiority of the Berger "4" for the brightness levels tested and the 0.20 second viewing time is appropriate for systems usage.

In a three-way comparison, Atkinson, Crumley and Willis (Ref. 10) evaluated the AND 10400 and Berger numbers with a set of numbers suggested by Brown et al. (Ref. 46) called AMEL (see Figures 61, 63 and 64). Two sets of conditions were tested: first, a simulated daylight condition with illuminations of 11, 24 and 34 Ft. Candles with a viewing time of 0.005 seconds and second, a red transillumination condition with brightnesses of 0.10, 0.30, 0.80, 1.60, 2.60 and 3.30 Ft. Lamberts at a viewing time of 0.20 seconds. Mean error scores indicated that the AMEL digits were significantly better than either of the other two styles for both the daylight and transillumination conditions.

Once again, a short exposure time limits the system application usefulness of the daylight condition, but the 0.20 second exposure time for the transillumination condition is realistic, and the data can be used where red lighting is acceptable.

Brown (Ref. 374) compared the legibility of Garamond Bold letters (see Figure 65) with NAMEL letters (see Figure 66). Nineteen letters (B, I, J, K, Q, V, & W excluded) were presented at a 0.20 second viewing time with brightnesses of 0.30, 0.80, 1.60, 2.60 and 3.30 Ft. Lamberts. The purpose in this study was to compare NAMEL letters, which are constructed with a uniform stroke-width-to-height and without serifs (a fine line or embellishment appearing chiefly at the ends of symbol strokes) with Garamond Bold letters, which are constructed with variable stroke-width-to-height and with serifs. Study results indicated that for accuracy of identification, NAMEL letters were superior to the Garamond Bold letters at all brightnesses levels tested, with the greatest differences falling at the 0.30 and 0.80 Ft. Lambert levels.

0 2 4 6 8
1 3 5 7 9

Figure 63. Berger Numerals.

0 2 4 6 8
1 3 5 7 9

Figure 64. AMEL Numerals.

ACDEFGHLMNOPRSTUXYZ

Figure 65. Garamond Bold Letters.

ACDEFGHLMNOPRSTUXYZ

Figure 66. NAMEL Letters.

The Mitre Corporation (Ref. 302), in attempting to develop a font which would be legible in different kinds of visual display systems, developed in the Lincoln/Mitre alphanumeric font (see Figure 67). Using four symbol brightnesses of 4, 6, 8, and 10 Ft. Lamberts (background brightness 1 Ft. Lambert), and a 0.01 second viewing time, the Lincoln/Mitre font was found to be statistically superior to the standard Leroy font (see Figure 62) in accuracy of identification for all brightness levels except the 4 Ft. Lambert condition.

It should be noted that this comparison was made at an extremely short viewing time which limits the application of the study conclusion. The data are interesting, however, in that the Lincoln/Mitre group was able to develop a font which, at least for the conditions tested, was superior to the standard Leroy.

A new approach to number legibility was studied by Lansdell in 1954 (Ref. 312). He constructed a set of numerals incorporating geometrical shapes designed to be easily recognized (see Figure 68). Comparing these numbers with Mackworth numbers (see Figure 60) at a 0.6 second exposure time and a brightness level of 10 Ft. Lamberts, Lansdell established that his numerals were significantly superior to the Mackworth for accuracy of identification. Two years later, Foley (Ref. 123) revised the Lansdell numbers (see Figure 69) and compared them again with the Mackworth numbers (see Figure 60). He found that for three illumination levels, 10, 30 and 50 Ft. Candles and three exposure times, 0.3, 0.8 and 1.3 seconds, the Foley numbers were significantly better than the Mackworth for accuracy of identification. No cross comparison of the Lansdell and Foley-Lansdell numbers has been reported.

Conclusion

Table 29 presents a summary of the non-electronic display font comparisons. Because of a lack of cross comparison studies, it is not possible to select a single most acceptable non-electronic display font. Shurtleff (Ref. 303) recommends the Mackworth alphanumerics as designed by the Lincoln Laboratory as the best choice available; yet both Lansdell and Foley have demonstrated that their relatively unorthodox new fonts are superior to the Mackworth for the conditions tested.

The Brown study (Ref. 374) indicated that, for letters, a uniform stroke-width-to-height, without serifs, was better for accuracy of identification than a variable stroke-width-to-height with serifs. Shurtleff (Ref. 303), in commenting on the Brown findings states, "it is recommended that letter styles featuring variable stroke widths and serifs be avoided in display situations, particularly when factors such as symbol brightness and exposure times are at marginal values". While

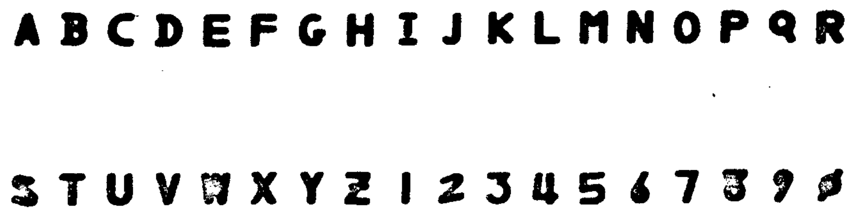


Figure 67. Lincoln/Mitre Alphanumerics.

Figure 68. Lansdell Numerals.

Figure 69. Foley Numerals.

Table 29. Non-Electronic Display Font Comparisons: A Summary.

Study	Fonts	Symbols Investigated
Mackworth (1944)	Mackworth[2]- AND 10400/Leroy	Alphanumerics
Showman (1966)	Leroy - Lincoln/Mitre[3]	Alphanumerics
Brown (1953)	Garamond Bold - NAMEL[2]	Letters
Atkinson (1952)	AND 10400 - Berger - AMEL[1]	Numbers
Lansdell (1954)	Lansdell[1]- Mackworth	Numbers
Foley (1956)	Foley/Lansdell[1]- Mackworth	Numbers

[1]Significantly better at either .05 or .01 level.
[2]Appeared better or a small percentage better.
[3]Shown to be superior, but comparison has limited utility due to the extremely short exposure times used in study.

these results appear to validate that serifs do not improve symbol legibility, the effect of variable stroke-width-to-height on symbol legibility is not sufficiently understood to form a conclusion. Both the Lansdell and Foley-Lansdell numerals incorporated variable stroke widths, and they were both shown to be superior for accuracy of identification to a standard Mackworth which used a fixed stroke width. Further investigation is deemed necessary before this issue may be reconciled.

The applicability of the non-electronic display research just discussed to an electronic display operational situation is complicated by the variations in alphanumeric legibility induced by the methods of symbol generation and display media. The NAMEL font, for example, was originally developed to optimize alphanumeric characters for aircrew station displays and was standardized in MIL-M-18012 (see Figure 70) and MS 33558 (see Figure 71). For a description of MIL-M-18012 number and letter dimensions see Table 30. MIL-M-18012 alphanumerics apply to both transilluminated and reflectively illuminated aircrew station displays and control panels; MS-33558 alphanumerics apply to aircraft instruments and dials. Transilluminated aircrew station display characters are somewhat like cathode-ray tube (CRT) characters because both emit light; however, CRT displays are luminescent and aircrew station displays are incandescent. Transilluminated characters are made up of solid areas of light passing through a translucent material, whereas electronically generated characters are varyingly composed of electronically generated raster matrices, dots or line segments. Thus, the method of symbol generation is responsible for the individual elements of composition defining the alphanumeric

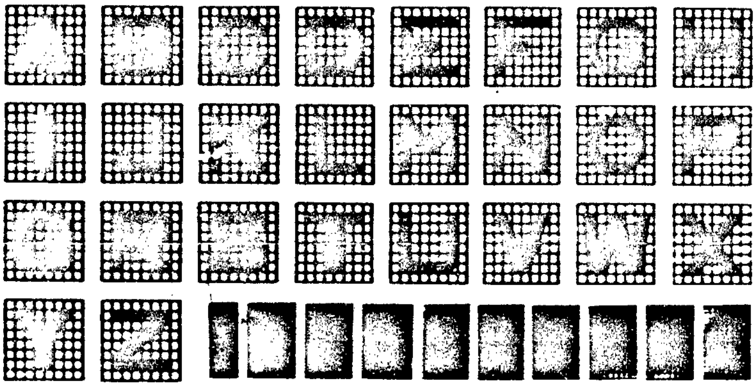


Figure 70. MIL-M-18012 Alphanumerics.

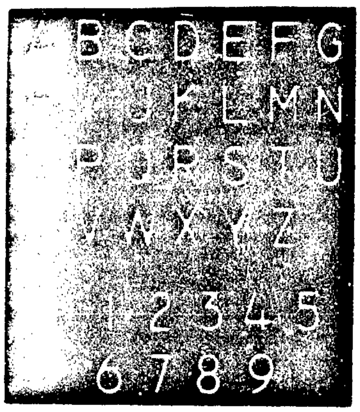


Figure 71. MIL Standard MS-33558 Alphanumerics.

Table 30. MIL-M-18012 Numeral and Letter Dimensions. (Adapted from Ref. 206)

DIMENSION	NORMAL USE TYPE I WHITE ON BLACK	NORMAL USE TYPE II WHITE ON GRAY	FOR EMPHASIS TYPE I WHITE ON BLACK	FOR EMPHASIS TYPE II WHITE ON GRAY
Height (H)	0.125 - 0.141" (15 - 17 min.)	0.156 - 0.172" (19 - 21 min.)	0.156 - 0.172" (19 - 21 min.)	0.188 - 0.204" (23 - 25 min.)
Width				
Numerals				
1	1 SW	1 SW	1 SW	1 SW
4	50 - 80% H	60 - 80% H	50 - 80% H	60 - 80% H
Others	40 - 70% H	60 - 70% H	40 - 70% H	60 - 70% H
Letters				
I	1 SW	1 SW	1 SW	1 SW
J, L	50 - 75% H	70 - 90% H	50 - 75% H	70 - 90% H
V	70 - 110% H	80 - 110% H	70 - 110% H	80 - 110% H
Others	60 - 100% H	80 - 100% H	60 - 110% H	80 - 100% H
Stroke Width (SW)				
Numerals	0.013 - 0.020" (1.7 - 2.3 min.)	0.020 - 0.025" (2.3 - 3.0 min.)	0.013 - 0.020" (1.7 - 2.3 min.)	0.020 - 0.025" (2.3 - 3.0 min.)
Letters	0.018 - 0.025" (2 - 3 min.)	0.025 - 0.030" (3 - 4 min.)	0.018 - 0.025" (2 - 3 min.)	0.025 - 0.030" (3 - 4 min.)
Spacing				
Between letters and numerals	1 SW	1 SW	1 SW	1 SW
Between words and numeral groups	1 standard charact. width	1 standard charact. width	1 standard charact. width	1 standard charact. width

character. Variations in shape, width-to-height, stroke-width-to-height, brightness contrast, etc., have been shown to affect legibility. Electronic display alphanumeric standards based on non-electronic display research represent an extrapolation which does not consider the large number of highly technical and interacting factors induced by the electronic system of symbol generation. Although current thinking (Refs. 373 and 206) specifies MIL-M-18012 and MS-33558 for electronic display devices, the following review of relevant research should be considered as it has been specifically conducted on alphanumeric fonts for electronic displays.

Electronic Display Studies of Font

One of the initial attempts to specify the optimum font for CRTs was conducted by Rowland and Cornog (Ref. 287), who examined a broad spectrum of commercially available alphanumeric fonts for use on a Spanrad Air Traffic Control television display screen. Basing their decision solely on a group subjective evaluation, these investigators concluded that none of the existing fonts was acceptable. In an attempt to produce an acceptable font, they designed a set of minimum size, uppercase alphanumeric characters which they called the Courtney font. Using the same group subjective technique, they compared their new Courtney font to the commercial fonts previously examined and decided the Courtney font was superior.

This asserted superiority was further validated by the follow-on study of Moore and Nida (Ref. 246), who employed a subjective method of evaluation to arrive at a parallel conclusion with Rowland and Cornog, namely, that for CRT application, the Courtney font was superior to all commercially available fonts.

Shurtleff and Owen (Ref. 306), however, observing that the subjective method of evaluation had been used in these tests, felt it necessary to investigate the legibility of the new Courtney alphanumerics using a more objective measure. They objectively compared the Courtney font (see Figure 72) with a standard Leroy font (see Figure 62) using a Miratel 14-inch video monitor connected to a 525-line Fairchild television camera. Table 67 presents the experimental conditions for this test. Legibility was measured in terms of both accuracy and speed of symbol identification. For symbol resolutions of 6, 8, 10 and 12 lines per symbol height, study results showed that with a small amount of practice the subjects identified the televised Courtney font less accurately and less rapidly than the Leroy font (Figures 151 and 152). With additional practice, however, the subjects found the Courtney and Leroy to be similar in accuracy and speed of identification (Figures 153 and 154). Statistically, the analysis indicated that only resolution was a statistically significant source of variance (see section on alphanumeric resolution). The differences between fonts were

Figure 72. Courtney Alphanumerics.

not statistically significant, nor was there a significant interaction between fonts and resolution. Shurtleff and Owen concluded, "There seems little to be gained by using the

> Courtney symbols for television, since the performance was not better than that obtained with the Leroy alphanumerics. Furthermore, the data suggest that the viewer must be given practice with the Courtney symbols, before his performance becomes as good as that obtained without practice with a standard lettering font." This conclusion appears to be

well justified for the results obtained in this study.

Shurtleff, Marsetta and Showman (Ref. 305) studied the standard Leroy and a revised Leroy font (the symbols, B,G,H,K, Q,S,Z,1,5,6,7 were modified for CRT usage) to determine the minimum symbol size (converted to visual angle of subtense) for good symbol identification at 10, 8, and 6 active raster scan lines per symbol height. See Table 74 for study details. Using a General Precision 945-line television camera and a Conrac 21 inch video monitor, minimum symbol sizes were established for both the standard and revised Leroy fonts for 85 and 99 percent correct levels of symbol identification. Examination of Table 75 shows the visual angles of subtense were similar for both fonts at each level of resolution. Statistically, symbol resolution was the only significant source of variance (see section on alphanumeric resolution). The average rates of symbol identification for the symbols identified 85 and 99 percent correctly are given in Table 76. These data indicate that

for both the standard and the revised Leroy fonts, the rate scores were similar at both 85 and 99 percent accuracy of identification levels for each value of resolution. Thus, for the conditions tested, neither of these fonts appears superior to the other for CRT usage. Of the eleven symbols modified in the revised style, only the H and B were recommended for inclusion in the standard Leroy font for use on television.

Bell (Ref. 25) compared two teletype fonts for legibility on a televised display. Using a 945-line General Precision Laboratories 820 camera and a Conrac CQE-14 monitor, the Long Gothic Style (Figure 73) was compared with the Murray Style (Figure 74) at resolutions of 12, 10, 8 and 6 active raster lines per symbol height. The experimental conditions for this test are presented in Table 71. The mean response times and the number of errors are given in Table 72 and 73 for each subject and both fonts. Inspection of these data led Bell to conclude that, for the resolutions tested, no difference existed between the legibility of Long Gothic and Murray alphanumerics. This analysis must be considered as trend information since a statistical analysis was not feasible due to the limited number of subjects used and a large intra-subject variance.

Conclusion

It appears that the standard Leroy font is acceptable for electronic display usage; however, this recommendation is made more from default of usable font comparisons than from any established superiority. In fact, a visual comparison between the Leroy (Figure 62) and MIL-M-18012 (Figure 70) alphanumerics indicates they are both fundamentally the same. Some differences are noted, however, for the C,I,J,M,4,5,6,9 and zero.

The small differences between these fonts and the relative availability of MIL-M-18012 alphanumerics led Ketchel and Jenney (Ref. 206) to state, "As to character font, stroke width,

> and width-to-height ratio, we also conclude that MIL-M-18012 is suitable as a goal for electronic and optically generated displays so long as allowances are made for departures from this norm due to the techniques of generation and the vertical and horizontal resolution of the display system. We have found very little evidence to indicate how much degradation in form and proportion is tolerable. We suspect that legibility will vary not only with symbol font, but also with such conditions of use as the amount of alphanumerically coded information, the operator's familiarity with the numeral and letter combinations, and the degree to which he can anticipate the occurrence of given statements. Here, too, we believe it is preferable to test these hypotheses through empirical studies."

A B C D E F G H I K L M N P Q R S T

U V W X Y Z 1 2 3 4 5 6 7 8 9

Figure 73. Long Gothic Alphanumerics.

A B C D E F G H I K L M N P Q R S T

U V W X Y Z 1 2 3 4 5 6 7 8 9

Figure 74. Murray Alphanumerics.

The relative suitability of MIL-M-18012 for electronically generated alphanumerics is an extrapolation based on the apparent similarity of this font to the standard Leroy which has been empirically tested. As previously mentioned, however, differences do exist between these fonts, but the effect on legibility of these differences has not been objectively determined and is therefore suspect. We heartily agree with Ketchel and Jenney that hypotheses concerning symbol legibility should be tested through empirical studies, and a good start would be to objectively determine the acceptability of MIL-M-18012 alphanumerics for electronic display application. Also, Ketchel and Jenney note that allowances should be made for differences in symbol generation techniques and resolution factors. Consideration should also be given to environmental factors such as vibration, acceleration and ambient illumination (see environmental variables section).

SYMBOL SIZE AND PROPORTION

This section examines the influence of height, width-to-height, and stroke-width-to-height on the legibility of alphanumeric symbols. Symbol height is presented as the visual angle of subtense formed by the height of the symbols at a particular viewing distance. Width-to-height considerations are presented as that percentage which symbol width is of symbol height. Stroke-width-to-height is likewise expressed as that percentage which stroke width is of height.

Because no acceptable electronic display studies were found in the literature for this topic (one exception in symbol height), the following non-electronic display studies are presented as supplemental material.

Symbol Height

Woodson et al. (Ref. 360) recently state, "In general, the larger the size of letters and numerals, the less we have to worry about backgrounds and illumination."

Limitations on available display space, considerations of information density, and general economic restraints often compel the systems designer to employ symbols no larger than those absolutely required to meet the legibility requirements of the system task. The following studies are presented to assist designers in establishing the minimum symbol size for legibility.

Howell and Kraft (Ref. 174) studied the relationship between symbol size, blur, and brightness contrast on the legibility of Mackworth alphanumerics. Symbol size was examined at 36.8, 26.8, 16.4 and 6.0 minutes of arc. No ambient illumination was specified but the surround was 3.5 Ft. Candles and the stimuli, prior to blur transition, varied from 46 to 134 Ft. Candles. Shurtleff (Ref. 303) tabled the Howell and Kraft data at each level of symbol size for the conditions of blur and brightness contrast (see Table 31). Blur was defined as the ratio between the width of the transition gradient from figure to ground and the stroke width of the letters. Performance was measured in terms of both accuracy and rate of symbol identification. Table 31 shows that for accuracy of identification with the indicated conditions of blur and contrast, 26.8 minutes of visual arc is required to maintain a consistently high percentage correct performance. At 16.4 minutes of arc, performance began falling off for the degraded brightness contrast and the heaviest blurred condition, although for the zero blur condition performance was approximately 97 percent which was equal to performance for zero blur and the larger 26.8 and 36.8 minutes of arc symbols. Performance did not substantially increase from the 26.8 to the 36.8 minutes of arc condition for any of the blur or brightness conditions. An examination of Table 31

Table 31. Accuracy and Rate of Symbol Identification for the Howell and Kraft Study. (Refs. 174 and 303)

Visual Angle in Minutes of Arc	Blur	Brightness Contrast (in Percent)	Percentage Correct	Symbols Per Second
36.8	2.82	3729	95.4	1.26
		1214	88.8	1.20
	1.66	3729	96.9	1.31
		1214	94.7	1.24
	0.55	3729	97.3	1.36
		1214	96.7	1.29
	0.00	3729	98.0	1.34
		1214	97.9	1.30
26.8	2.82	3729	96.4	1.27
		1214	93.6	1.21
	1.66	3729	97.7	1.34
		1214	96.4	1.22
	0.55	3729	97.9	1.36
		1214	97.3	1.31
	0.00	3729	98.3	1.34
		1214	97.3	1.32
16.4	2.82	3729	94.2	1.16
		1214	87.4	1.03
	1.66	3729	96.9	1.30
		1214	93.0	1.10
	0.55	3729	96.8	1.28
		1214	96.3	1.21
	0.00	3729	97.6	1.29
		1214	96.3	1.26
6.0	2.82	3729	47.0	.70
		1214	23.2	.66
	1.66	3729	48.3	.72
		1214	30.0	.66
	0.55	3729	57.7	.82
		1214	48.3	.66
	0.00	3729	65.3	.78
		1214	50.8	.65

indicates that, for rate of identification, there was no substantial difference between the 36.8 and 26.8 minutes of arc conditions. From 26.8 to 16.4 minutes of arc, however, a 7.3 percent average decrease in performance was obtained. Thus, for both accuracy and rate of symbol identification across the blur and brightness contrast levels tested, the 26.8 minutes of arc (.22 inches symbol height at a 28-inch viewing distance) condition appears to maintain consistently high performance. If no blur is anticipated in the design, then 16.4 minutes of arc (.13 inches symbol height at a 28-inch viewing distance) is adequate for systems application.

Shurtleff, Marsetta and Showman (Ref. 305) performed a study to determine the visual size (in minutes of arc) of Leroy and revised Leroy alphanumerics required on television for 99 and 85 percent symbol identification at resolutions of 10, 8 and 6 active scan lines per symbol height. For a description of the experimental variables in this study see Table 74, and for a more detailed review of this study see page 364 in the section on resolution. Table 75 shows that the visual angles of subtense were similar for the two fonts at each value of symbol resolution. Statistical analysis indicated that a symbol resolution of 6 lines differed significantly at the .01 level from both 8 and 10 lines, but that 8 and 10 lines did not differ significantly from each other. This would suggest for resolutions of 8 to 10 active scan lines per symbol height that a minimum visual angle of approximately 15 minutes of arc should be used with Leroy alphanumerics for a 99 percent accuracy of identification level. If 6 scan lines are used, then a minimum visual angle of 36 minutes of arc should be used for 99 percent accuracy. Rate of symbol identification was similar for all symbol resolutions and both fonts at the 85 and 99 percent correct symbol identification levels (see Table 76).

Conclusion

The Howell and Kraft data indicate for the non-blurred conditions that a visual size (visual angle of subtense in minutes of arc) of 16.4 minutes of arc (.13 inches symbol height at a 28-inch viewing distance) is adequate for approximately 97 percent accuracy of identification. Assuming this data establishes a reasonable visual size for solid line printed symbols, the visual size of 15 minutes of arc determined by Shurtleff et al., on a television system, suggests that 8 to 10 active scan lines of resolution are adequate to produce performance comparable with the printed symbols. It is therefore recommended that 15 minutes of arc be considered the minimum visual size for alphanumeric symbols displayed on a CRT with a resolution of 8 to 10 (or more) active television scan lines per symbol height. Should the symbols be subject to blurring (up to 2.82) the symbol size should be raised to a minimum of 27 minutes. Symbols presented on a television system employing a resolution

of 6 active scan lines per symbol height should use a minimum visual size of 36 minutes. For consideration of the minimum visual size for alphanumeric symbols viewed under conditions of vibration, acceleration, extremes of brightness or contrast ratio, consult the appropriate sections of this report.

Symbol Width to Height

Brown (Ref. 374) studied the effect of variations in width-height proportion upon the legibility of capital block letters to be used in aircraft cockpit plastic lighting plates. Four widths of 55, 70, 85 and 100 percent of symbol height were investigated for brightnesses of .30, .80, 1.60, 2.60 and 3.30 Ft. Lamberts at .20 (see Table 32) and .04 second (see Table 33) exposure times. These data indicated for the conditions tested that increases in symbol width result in improved legibility. It should be noted, however, that this study was conducted under simulated night conditions and that, as indicated, the luminance values were quite small. This factor, combined with the short exposure times used, contributed to the generally high percentage of errors across all test conditions. Since accuracy of identification error percentages must approach zero for effective system considerations of legibility, it is suggested that these data be used cautiously.

Soar (Ref. 319) examined width-to-height and stroke-width-to-height in numeral legibility. Because he was interested in studying the symbol proportion effects of width-to-height on legibility, he maintained the rectangular area covered by any given number constant for the numeral width-to-height tested. The stroke-width-to-height was, however, varied for each symbol width-to-height considered. Four widths of 30, 45, 60 and 75 percent of symbol height were studied (symbol height varied and the viewing distance was not specified), using AMEL numerals, established by Brown, Lowery and Willis (Ref. 46), at a .04 second exposure time and one Ft. Candle stimulus illumination. Results indicated that for accuracy of identification, differences in legibility due to stroke width were not significant, except for the 8. Soar also emphasized the fact that the interaction of width-height proportions and stroke-width-to-height was in no case significant. This led to his conclusion that subsequent studies of width-height proportions could be conducted without considering stroke width. His results further indicated that for accuracy of identification, a width of 75 percent of symbol height was optimum for the values tested (see Table 34).

Why this author concluded that 75 percent width-to-height was superior is not apparent because 6 out of the 10 digits were superior at the 60 percent width-to-height level in comparison to the 75 percent width-to-height level. Extremely high error rates (92 percent and up), a short exposure time and a low illumination level limit the application of any study conclusion to systems usage. This study was included in this section because of the dearth of acceptable and usable studies on width-to-height proportion.

Table 32. Total Number of Errors and Percentage Error for Various Width-Height Proportions with Transillumination and .20 Second Exposure Time. (Adapted from Brown, Ref. 374)

Variable W/H (Percent)	Datum	Luminance of Transillumination (Ft. L.) .30	.80	1.60	2.60	3.30
100	#errors	36	36	30	42	24
	%errors	15.00	15.00	12.50	17.50	10.00
85	#errors	49	39	43	37	39
	% errors	20.42	16.25	17.92	15.[illegible]	16.25
70	#errors	67	63	54	53	61
	%errors	27.92	26.25	22.50	22.08	25.25
55	#errors	131	90	89	97	77
	%errors	54.58	37.50	37.08	40.42	32.08

Table 33. Total Number of Errors and Percentage Error for Various Width-Height Proportions with Transillumination and .04 Second Exposure Time. (Adapted from Brown, Ref. 374)

Variable W/H (Percent)	Datum	Luminance of Transillumination (Ft. L.) .30	.80	1.60	2.60	3.30
100	#errors	129	61	36	30	31
	%errors	53.75	25.42	15.00	12.50	12.92
85	#errors	152	69	53	46	37
	%errors	63.33	28.75	22.08	19.17	15.42
70	#errors	166	95	69	60	57
	%errors	69.17	39.58	28.75	25.00	23.75
55	#errors	203	140	116	112	96
	%errors	84.58	58.33	48.33	46.67	40.00

Table 34. Average Number Correct Responses Per Subject for Various Numeral Width-to-Height Percentages. (Adapted from Soar, Ref. 319)

	Width-to-Height in Percent			
Numeral	30	45	60	75
0	1.26	1.19	2.32	3.74
0*	--	--	2.45	4.06
1	7.06	6.28	7.20	6.09
2	3.90	5.16	5.50	5.07
3	2.92	4.52	4.87	5.87
4	6.04	7.52	7.71	7.70
5	4.25	4.42	3.42	2.92
6	3.45	5.17	5.69	6.26
7	5.53	7.62	7.88	7.77
8	2.69	3.19	3.74	3.39
8*	--	--	3.88	3.57
9	3.67	7.19	6.51	6.77

*Partial Data

Conclusion

While no conclusion for systems application may be definitively drawn from these studies due to short exposure times, high error rates, and confusing study interpretations, it is in general thought that symbol widths on the order of 50 to 100 percent of height are adequate to optimize symbol legibility. If significant departures from these values are contemplated, then empirical investigations should be conducted to determine the effect on legibility. Overall study results also indicate that a larger width-to-height percentage improves symbol legibility under dim lighting conditions.

Symbol Stroke Width-to-Height

Crook, Hanson and Weisz (Ref. 96) investigated the factors influencing the legibility of type found on aeronautical charts under cockpit illumination (.082 Ft. Candles ambient). Of specific concern were the effects on accuracy and rate of symbol identification for letters of three sizes, three brightness contrasts (symbol and background luminance were not specified) and two symbol spacings in conjunction with three stroke widths. Table 35 presents the results of this study.

Table 35. Mean Scores on Oral Reading Task with Capital Letters. (Refs. 96 and 303)

Visual Angle in Minutes of Arc	Brightness Contrast Percent	Stroke Width in Percent of Symbol Height	Spacing in Percent of Symbol Height	Accuracy of Identification in Percent Correct	Rate of Identification in Symbols Per Second
22.0	94	9.8	35.6	99.7	3.2
			63.2	99.6	3.1
		20.1	35.6	99.1	3.2
			63.2	99.1	3.3
		30.0	35.6	98.8	3.1
			63.2	99.1	3.1
	90	9.8	35.6	99.1	2.8
			63.2	99.1	2.7
		20.1	35.6	99.4	3.1
			63.2	99.8	3.1
		30.0	35.6	99.1	3.1
			63.2	98.8	2.9
	81	9.8	35.6	94.7	1.7
			63.2	95.9	1.7
		20.1	35.6	99.1	2.8
			63.2	98.8	2.7
		30.0	35.6	96.8	2.3
			63.2	95.6	2.2
16.0	94	9.8	35.6	98.8	2.7
			63.2	98.9	2.8
		20.1	35.6	99.4	3.1
			63.2	99.7	3.1
		30.0	35.6	97.3	2.7
			63.2	97.9	2.7
	90	9.8	35.6	97.3	2.2
			63.2	97.1	2.3
		20.1	35.6	99.1	2.8
			63.2	98.8	2.7
		30.0	35.6	96.7	2.6
			63.2	96.1	2.4
	81	9.8	35.6	81.6	1.8
			63.2	78.2	1.9
		20.1	35.6	95.3	2.1
			63.2	95.3	2.1
		30.0	35.6	88.8	1.8
			63.2	87.5	1.6
11.0	94	9.8	35.6	94.0	1.7
			63.2	91.8	1.7
		20.1	35.6	96.7	2.3
			63.2	94.9	2.3
		30.0	35.6	89.8	1.9
			63.2	90.2	1.8
	90	9.8	35.6	81.1	1.9
			63.2	76.1	1.1
		20.1	35.6	93.7	1.8
			63.2	89.4	1.7
		30.0	35.6	86.8	1.6
			63.2	84.3	1.4
	81	9.8	35.6	62.7	1.2
			63.2	53.9	1.3
		20.1	35.6	75.9	1.8
			63.2	68.0	1.9
		30.0	35.6	65.8	0.8
			63.2	56.3	0.8

For accuracy of identification it was observed that, generally speaking, a stroke-width-to-height of 20 percent was best for the conditions tested. Stroke-width-to-height did not appear to affect accuracy of identification when brightness contrast was above 90 percent and the visual angle of subtense for the symbols was 22 minutes of arc. For rate of identification, Table 35 indicates that stroke-width-to-height had little effect when the visual angle of subtense for the symbols was 22 minutes of arc and the brightness contrast was 94 percent. For the remaining values of visual angle and brightness contrast, a stroke-width-to-height of 20 percent resulted in the highest rate of symbol identification.

Crook, Hanson and Weisz (Ref. 95) further studied letter stroke-width-to-height for two levels of symbol-width-to-height, three symbol spacings (different three for each symbol-width-to-height) and two levels of test object illumination (see Table 36). Letters averaged .064 inches in height and were viewed at 14 inches subtending a visual angle of 15.71 minutes of arc. For both levels of symbol-width-to-height and the high test object illumination level, accuracy of identification approached the 99 percent correct level of performance. The only systematically degraded error score performance obtained was for the low illumination level and the narrowest stroke-width-to-height. Thus, stroke-width-to-height appears to influence legibility only under dim lighting conditions. Across all experimental conditions, error score performance differences for stroke-width-to-height were small and no significant differences were reported. Likewise, for rate of symbol identification, no stroke-width-to-height effect was reported.

In the previous section on symbol-width-to-height, the study performed by Soar (Ref. 319) on numeral legibility established that for accuracy of identification, stroke-width-to-height did not affect legibility except for the number 8. Soar also pointed out that in no case was the interaction of width-to-height and stroke-width-to-height significant. See this study in the section on symbol-width-to-height for further details and conclusions.

The Aeronautical Medical Equipment Laboratory conducted a series of studies to determine the requirements for letters, numbers and markings to be used on transilluminated control panels in the cockpits of military aircraft. Brown and Lowery (Ref. 45) conducted the first study of this series on the effects of stroke-width-to-height, symbol brightness and exposure time on legibility. Five values of stroke width, 7, 10, 13, 17 and 20 percent of symbol height, five values of symbol brightness, .33, .79, 1.63, 2.60 and 3.34 Ft. Lamberts, and two exposure times, .20 and .04 seconds, were tested. Fourteen capital letters, A, C, D, E, F, H, L, N, O, P, T, X, Y and Z, were presented in groups of three at a viewing distance

Table 36. Mean Scores on Oral Reading Task with Capital Letters. (Refs. 95 and 303)

Symbol Width in Percent of Height	Spacing in Percent of Symbol Height	Stroke-Width Percent of Symbol Height	Illumination in Ft. Candles	Accuracy of Identification in Percent Correct	Rate of Identification in Symbols Per Second
86.3	8.1	9.8	13.6	99.4	2.9
			.082	94.5	2.1
		21.1	13.6	99.8	3.1
			.082	98.8	2.7
		30.0	13.6	99.6	3.1
			.082	98.6	2.6
	35.6	9.8	13.6	99.7	3.3
			.082	98.9	2.7
		21.1	13.6	99.8	3.4
			.082	99.3	3.0
		30.0	13.6	99.9	3.1
			.082	97.5	2.7
	63.2	9.8	13.6	100.0	3.3
			.082	98.6	2.5
		21.1	13.6	99.8	3.2
			.082	99.2	3.0
		30.0	13.6	99.7	3.4
			.082	98.2	2.8
59.8	4.8	8.8	13.6	98.2	2.5
			.082	89.5	1.5
		15.5	13.6	99.1	2.5
			.082	95.6	1.9
		20.3	13.6	99.6	2.6
			.082	94.7	1.8
	25.4	8.8	13.6	99.7	3.0
			.082	97.3	2.2
		15.5	13.6	99.7	3.1
			.082	97.0	2.6
		20.3	13.6	99.3	3.2
			.082	95.8	2.3
	46.1	8.8	13.6	99.2	3.3
			.082	96.8	2.2
		15.5	13.6	99.7	3.1
			.082	97.7	2.5
		20.3	13.6	99.8	3.2
			.082	95.5	2.3

of 28 inches. All letters were .156 inches in height which subtended a visual angle of 19.15 minutes.

For the .04 second exposure time (see Table 37), stroke-width-to-height did not affect accuracy of identification for symbol brightnesses of 1.63, 2.60 and 3.34 Ft. Lamberts. For the remaining symbol brightnesses of .33 and .79 Ft. Lamberts at the .04 second exposure time, stroke widths of 6.7 and 10 percent of symbol heights resulted in performance significantly less than the stroke widths of 13.3, 16.7 and 20.0 percent of symbol height. At the .20 second exposure time (see Table 38), symbol stroke-width-to-height had no significant effect on accuracy of identification for the brightnesses tested.

While both exposure times used are shorter than observed for pilot eye fixation, it is interesting to note that for the .2 second exposure time stroke-width-to-height had no effect on legibility for any of the brightness levels tested. Only when the exposure time was reduced to .04 seconds and a dim illumination of .33 and .79 Ft. Lamberts did stroke-width-to-height affect symbol legibility.

Conclusions

Throughout the studies presented, stroke-width-to-height appears consistently to affect legibility when test conditions are degraded in terms of brightness, brightness contrast and exposure time. Results from the Crook et al. (Ref. 96) and Brown et al. (Ref. 45) studies indicate a stroke width of from 13.3 to 20 percent of symbol height is optimum for the conditions of brightness and exposure time tested. When brightness is increased and exposure times slowed, stroke-width-to-height does not appear to have an effect on either accuracy or rate of symbol identification.

Table 37. Mean Percent Correct Scores for Reading Transilluminated Block Style Capital Letters When Exposure Time is .04 Second. Each Subject Read Five Cards of Three Letters for Each Stroke Width and Brightness Combination. (Adapted from Brown et al., Ref. 45)

Stroke Width to Height (in Percent)	Brightness of Transillumination (Ft. Lamberts) .33	.79	1.63	2.60	3.34
6.7	.60	28.40	59.40	70.73	79.74
10.0	2.87	44.40	65.80	79.40	79.13
13.3	16.87	59.13	69.87	78.27	81.73
16.7	21.13	63.80	75.94	77.67	82.60
20.9	24.33	62.87	75.34	80.60	73.60

Table 38. Mean Percent Correct Scores for Reading Transilluminated Block Style Capital Letters When Exposure Time is .20 Second. Each Subject Read Five Cards of Three Letters for Each Stroke Width and Brightness Combination. (Adapted from Brown et al., Ref. 45).

Stroke Width to Height (in Percent)	Brightness of Transillumination (Ft. Lamberts) .33	.79	1.63	2.60	3.34
6.7	80.80	90.00	89.47	92.80	96.93
10.0	84.07	90.27	90.53	91.27	91.00
13.3	82.80	91.27	92.53	91.80	89.73
16.7	85.13	91.53	92.07	91.80	92.07
20.0	89.20	87.93	85.13	90.54	87.20

SYMBOL SPACING

Symbol spacing is a measure of the distance between vertical tangents erected at the outer limits of adjacent symbols (Ref. 303).

Crook, Hanson and Weisz (Ref. 96) investigated two symbol spacings in conjunction with three symbol sizes (visual angles), three brightness contrasts and three stroke-width-to-heights. Symbol spacing of 35.6 and 63.2 percent of symbol height were studied for both accuracy and rate of symbol identification across the conditions indicated in Table 35. In terms of accuracy of identification, these two levels of symbol spacing appeared to have no effect until (a) the visual angle was reduced to 16 minutes of arc, and (b) the poorest brightness contrast conditions were used. For these conditions the 35.6 percent spacing averaged a 1.23 percent superiority over the 63.2 percent spacing condition. Further decreasing the visual angle to 11 minutes of arc resulted in improved performance at each successively reduced level of brightness contrast for the 35.6 percent symbol spacing, and this held true until a 8.07 percent average superiority was reached for the poorest brightness contrast.

Crook, Hanson and Weisz (Ref. 95) further studied symbol spacing for two width-to-heights, three stroke-width-to-heights (different three width-to-heights for each symbol spacing) and two illumination levels (see Table 36). Symbol spacings of 8.1, 35.6 and 63.2 percent symbol height for the 86.3 symbol-width-to-height and spacings of 4.8, 25.4 and 46.1 percent symbol height for the 59.8 symbol-width-to-height were studied for both accuracy and rate of symbol identification. No differences in accuracy of identification was observed for any of the symbol spacings tested. For rate of symbol identification the data shows a slight trend toward an increase for each successively wider symbol spacing.

Conclusion

The Crook et al. (Ref. 95 and 96) studies indicate that accuracy of identification for letters is not affected by symbol spacing for the conditions tested when symbols subtend visual angles greater than 16 minutes of arc. When the visual angle is reduced to 16 minutes of arc or below and is in conjunction with a poor brightness contrast, then the narrower 35.6 percent symbol spacing improves accuracy of performance. For rate of symbol identification, however, the second of the Crook et al. (Ref. 95) studies indicates that a wider symbol spacing (up to 63.2 percent) results in improved speed. It appears that symbol spacings ranging between 26 and 63 percent of symbol height result in only small differences in both speed and accuracy of

identification. If design requirements demand symbol spacings outside of this range it is suggested that the effect on legibility be empirically determined prior to design implementation.

WORDS

Due partly to the difference in availability of contextual cues, the findings for single symbols cannot be generalized to words and vice versa. Therefore, separate ligibility recommendations for words used in CRT type display systems need to be established. Kosmider (Ref. 375) ascertained observer's ability to read five-letter words with individual symbol resolutions of 10, 7 and 5 active scan lines per symbol height. Twelve subjects viewed the words on a standard commercial television display. A total of 100 commonly used words were shown to each subject at a constant visual size of 16 minutes of arc. The results indicated nearly perfect (99 percent) accuracy for words composed of solid stroke letters and for words composed of 10 or 7 lines per word height. Accuracy dropped to 97 percent for resolutions of 5 lines per word height.

Conclusion

This study does not specify some of the important display variables necessary for accurate design specification of word legibility for CRTs. Since other research in this area is also inadequate to establish meaningful design parameters, it is recommended that additional study be given this problem.

EDGE (OFF-CENTER OF TUBE) DISPLAYED SYMBOLOGY

Shurtleff, Marsetta and Showman (Ref. 305), in the second part of a three-part study, investigated the effect of viewing alphanumeric symbology at the edge of a television raster (to the side of the tube center). Four subjects who had been shown a symbol resolution of 10 lines in the first part of the experiment, cited previously (see Page 167), were retested under the same circumstances, with the exception that the symbols were shown at the left edge of the CRT. Table 39 displays the results of the symbology viewed at the edge of the tube and the results for center viewing for the same subjects from part one of the experiment. Table 74 lists the experimental conditions for this test.

A comparison of the edge displayed with the center displayed symbology indicates that the visual angle of subtense for

Table 39. Symbol Sizes and Rates for Center and Edge Displays.

Subject	85 Percent Identification Accuracy				99 Percent Identification Accuracy			
	Visual Angle (Min.)		Rate (Symbols/Sec.)		Visual Angle (Min.)		Rate (Symbols/Sec.)	
	Raster Position		Raster Position		Raster Position		Raster Position	
	Center	Edge	Center	Edge	Center	Edge	Center	Edge
1	7.62	8.14	1.49	1.63	12.66	14.72	4.54*	2.17
2	6.90	7.14	1.28	1.59	11.86	12.31	1.26	2.50
3	8.10	8.41	1.06	1.33	15.14	17.31	1.33	1.41
4	7.34	7.39	1.20	1.54	11.07	12.16	1.92	2.44
Mean	7.49	7.77	1.26	1.52	12.68	14.12	2.26	2.13

*The identification rate values were derived by mathematical extrapolation of obtained points, therefore, extreme values like this sometimes occur.

99 percent accuracy of identification needs to be increased 1.5 minutes or about 11 percent (.28 minutes or 4 percent for 85 percent accuracy of identification) over that required for the same accuracy when symbols are viewed at the center of the raster.

Conclusion

To maintain a 99 percent accuracy of identification the viewing size (visual angle of subtense in minutes of arc) should be about 11 percent greater for symbols at the edge of the raster than for symbols at the center.

VIEWING ANGLE

Viewing angle refers to the angular relationship expressed in degrees between the center point on the display face and the viewer's visual axis. For example, normal viewing occurs at zero degrees, which is when the visual axis is in line with the display center point and perpendicular to the screen face.

Very little directly applicable CRT research has been conducted on viewing angle. The single exception is an article by Seibert (Ref. 376) which indicated that televised alphanumerics could be viewed up to 19 degrees from the normal viewing axis before a decrease in accuracy of identification occurred. Some loss in accuracy of identification was observed to occur for a critical angle of between 19 and 38 degrees from the normal viewing axis.

For additional information relating viewing angle to considerations of resolution see section on visual acuity.

SYMBOL BLUR

Blur is defined as the ratio between the width of the transition gradient from figure to ground and the symbol stroke width.

Howell and Kraft (Ref. 174) examined symbol blur in conjunction with symbol size and brightness contrast for both accuracy and rate of symbol identification. Symbol blur was studied at ratios of 2.82, 1.66, .55 and 0.00. Symbol size was examined at 36.8, 26.8, 16.4 and 6.0 minutes of arc. No ambient illumination was specified, but the surround was 3.5 Ft. Candles and stimuli prior to blur transition varied from 46 to 134 Ft. Candles. Brightness contrast levels of 3,729 and 1,214 percent

were also studied. Table 31 in the section on symbol height presents the results for this experiment.

Generally, accuracy and rate of symbol identification were better for the larger symbols. Unacceptable performance was obtained for both blur and non-blur conditions when symbol size was reduced to 6.0 minutes of arc.

Blur more seriously affected the smaller brightness contrast of 1,214 percent. For accuracy of identification this contrast at the larger visual angles produced only a 4 to 10 percent decrease; for the 6.0 minute of arc condition a 27.6 percent decrease occurred. Just the opposite decrease occurs, however, for rate of symbol identification; for the larger visual angles a 0.10 to 0.23 second decrease in rate occurs, but for the 6.0 minute of arc condition a very small .01 second decrease was found.

For the higher contrast of 3,729 percent, essentially the same qualitative phenomena occur, but to a much smaller degree.

From this study it may be concluded that symbol blur tends to be less detrimental to letter legibility when symbols are larger and contrast percentage higher. For additional considerations of CRT image blur, see section on display resolution considerations.

Conclusion

Little can be gleaned from this non-CRT study for CRT application. It may be generally prescribed for design purposes that symbol blur be avoided. When this is not possible, enlarged letters and an increased contrast percentage will facilitate legibility, but the degree of facilitation cannot be predicted.

MATRIX SYMBOL GENERATION TECHNIQUES

Introduction

Matrix or dot pattern character generation techniques employ dots or line segments located at selectable points within a matrix. There are numerous types of matrix pattern generators including fixed or variable matrix points with computer stored dot positions provided either digitally with associated digital-to-analog conversion circuitry or in analog with digital control circuits.

The first division of this section deals with CRT matrix symbology utilizing digital storage and digital to analog conversion circuitry. The second division reports studies relating

to solid state matrix symbology which incorporates fixed analog components with digital control circuitry.

Cathode Ray Tube Matrix Symbols

For CRT fixed-format matrix pattern generator, all dots within the matrix are pulsed in incremental steps by the electron beam, but only those which contribute to the selected character are unblanked. The blanked and unblanked dots composing the desired character are selected by the control logic as a function of the character selection code.

CRT stroke patterns are another matrix generation technique. Stroke symbols are a function of an unblanked electron beam moving as a stylus to define the shape of a given symbol. The line segments forming the symbol are defined by fixed end points within a matrix.

The following selected studies present legibility information which applies to CRT matrix formed alphanumeric characters.

A recent study was conducted by Vartebedian (Ref. 335) on the relationship between legibility and symbol generation techniques for CRTs. Two character generation techniques were evaluated: dot matrix and stroke pattern. Dot matrices of 5 points wide by 7 high (5 x 7) and 7 points wide by 9 high (7 x 9) were compared with stroke characters made up of continuous line segments generated within a 9 wide by 9 high (9 x 9) matrix. Segmented symbols utilized up to 31 individual stroke segments whose maximum length was two either vertical or horizontal matrix squares.

Study comparisons were made of the following parameters: (1) symbol generation technique; symbols drawn with dots vs. symbols drawn with continuous strokes, (2) dot matrix size: 5 x 7 vs. 7 x 9 dot matrices, (3) symbol orientation: vertical symbol vs. symbols slanted 20° (right) from vertical, and (4) dot geometry, circular dot vs. vertically elongated dots. Table 40 presents the experimental conditions in this study.

For accuracy and speed of identification (see Table 41), the data indicated for the four comparisons made that the dot matrices were significantly (all statistical significances in this study are at the .01 level) superior to the stroke symbol generation technique (5 x 7 not significantly better than stroke for speed of identification) and the 7 x 9 dot matrix was significantly better than the 5 x 7. For accuracy of identification, a vertical symbol orientation was significantly superior to the slanted for both the stroke and elongated dot generation techniques. For speed of symbol identification, the vertical orientation for the elongated dots was significantly better than the slanted, but no significant difference was found between the vertical and slanted stroke symbols. Also, circular dots were

Table 40. Experimental Conditions for Vartebedian Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 23	Horizontal Spacing: Not specified
Visual Characteristics of Subjects: Not specified	Symbol-Background Relation: Light/Dark
	Symbol Brightness: 11 Ft. Lamberts
	Background Brightness: 2 Ft. Lamberts
Number of Symbols: 26 Letters 10 Numbers	Brightness Contrast: 450 Percent
Symbol Exposure Time: Response Time to Identification	Ambient Illumination: Not specified
Symbol Font or Style: Stroke Font was similar to Leroy	Symbol Visual Size: 17.2 Minutes of Arc
Symbol Width/Height: 75 Percent	Viewing Distance: 28 inches
Symbol Stroke Width/Height: Not specified	Viewing Angle: Zero degrees

superior to elongated dots for accuracy and speed of identification across all comparisons. At the end of the experiment an interesting subjective evaluation was made of the study symbols. Subjects were asked to rank-order the six alphanumeric configurations according to legibility and aesthetic appearance where 1 was best and 6 was worst. Table 42 presents the average ranking given by the 23 subjects. This evaluation indicated that subjects much preferred the appearance of the vertical stroke symbols and considered the vertical stroke and 7 x 9 circular dot matrix superior in legibility.

It is noted that the subjective data are considerably different from the objective performance data. Vertical stroke symbols were subjectively considered to be superior in legibility and were most preferred in appearance, but empirical testing indicated that the vertical stroke symbols are rank ordered third best in errors and second in viewing time. While the 7 x 9 circle dot was subjectively considered to be second best in both legibility and appearance, it was empirically determined to be superior in both error scores and viewing time.

From Vartebedian's results and summary it may be concluded that slanted symbols and elongated dot matrices should be avoided, that dot matrices are as good or better than stroke generated symbols, and that a 7 x 9 dot matrix is better than a 5 x 7.

In an unpublished preliminary communication, Anderson (Ref. 7) reports legibility tests for dot matrix alphanumerics viewed on a Hewlitt-Packard 180-A oscilloscope. For a description of the experimental variables see Table 44. Using both accuracy and rate of symbol identification as performance measures of legibility, five subjects viewed symbols at a .10 second exposure time. All symbols were formed in a 7 x 9 matrix and were .095 inches in height and subtended 7 minutes of arc at a viewing distance of 46.56 inches. A Lincoln-Mitre font was used and the particular configuration is presented in Figure 75.

Results for this test are presented in Table 43 and indicate for the conditions tested that subjects were capable of 98.14 percent accuracy and 120.64 characters per minute. Detailed analysis of confusion matrices (see Table 45) indicated that most errors occurred for only a few symbols. The primary confusions were the zero with the letter O, V with the U and the I with the 1.

Experimental limitations including no reported luminance values and an extremely rapid exposure time limit this study's design applicability. It may, however, be concluded that CRT viewed Lincoln-Mitre alphanumeric dot matrices are highly legible even for the relatively small symbols presented.

Table 41. Average Viewing Time and Error Rates for the Six Conditions.

Condition	Viewing Time (Seconds)	Errors (Percent)
5 x 7 Circle Dot	0.697	2.9
7 x 9 Circle Dot	0.602	2.6
Vertical Stroke	0.659	4.5
Slant (20°) Stroke	0.677	6.7
7 x 9 Elongated Dot	0.678	3.2
7 x 9 Slant (20°) Elongated Dot	0.814	7.7

Table 42. Average Ranking 1-Best to 6-Worst for the Six Conditions.

Condition	Legibility	Appearance
Vertical Stroke	2.5	1.9
7 x 9 Circle Dot	2.6	2.7
7 x 9 Elongated Dot	3.3	3.6
5 x 7 Circle Dot	3.7	4.3
Slant Stroke	4.1	3.7
7 x 9 Slant Elongated Dot	4.8	4.9

Table 43. Accuracy and Rate of Symbol Identification.

Subject	Accuracy (Percent)	Rate (Symbols/Minute)
1	97.64	109.19
2	98.61	128.43
3	97.36	116.70
4	99.31	131.35
5	97.78	119.97
Average	98.14	120.64

Table 44. Experimental Conditions for the Anderson Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 5	Horizontal Spacing: Not specified
Visual Characteristics of Subjects: 20/20 Acuity for American Optical Reading Tests	Symbol-Background Relation: Light/Dark
	Symbol Brightness: Not specified
	Background Brightness: Not specified
Number of Symbols: 26 Letters 10 Digits	Brightness Contrast: Ratio given as 10:1
Symbol Exposure Time: Response time to identification	Ambient Illumination: 30 Ft. Candles
Symbol Font or Style: Lincoln/Mitre adapted to a 9 x 7 dot matrix	Symbol Visual Size: 7 Minutes of Arc
Symbol Width/Height: Varied from 55.6 to 77.8% except for the 1 and I which were 11.1 and 33.3%	Viewing Distance: 46.56 inches
Symbol Stroke Width/Height: Not specified	Viewing Angle: Zero degrees

Table 45. Confusion Matrix for Anderson Study.

Alphanumeric Symbols Presented (Test Stimuli)

Alphanumeric Responses Confused with Stimuli

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	1	2	3	4	5	6	7	8	9	Ø	
A																																					
B																										1											1
C																																					
D																																					
E																																					
F																																					
G																																1					1
H																																					
I																											6										6
J																																					
K																																					
L																																					
M								1																													1
N																																			1		1
O																																					
P																															1						1
Q	1						1								1																					1	4
R																	4																				4
S																																					
T																																					
U																						13															13
V																										1											1
W																																					
X																																					
Y																							1														1
Z																			1									1						1			3
1									1					1																							3
2																										2											2
3																																		1			1
4																																					
5																																					
6												2																									2
7																																					
8		1									1																										2
9																	1																				1
Ø							2								17																						19
	1	1					3	1	1		1	2		2	18		5		1			13	1			4	6	1			1	1		2	1	1	67

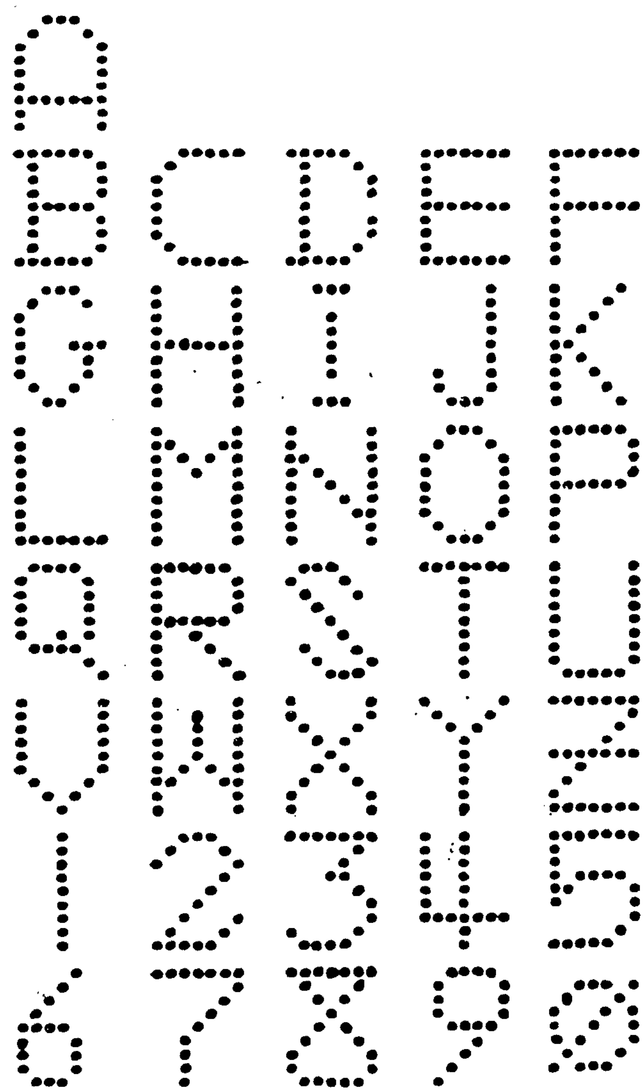


Figure 75. Lincoln/Mitre Dot Matrix Alphanumerics.

Gibney (Ref. 138), in a review of the literature dealing with the legibility of segmented versus standard numerals, found when standard arabics are compared with segmented numerals they are usually found to be more legible. Gibney's thesis is that before this conclusion may be granted, a careful look must be taken at the subject's response task complexity. Gibney reviewed a series of legibility studies where the differences between standard arabic numerals and segmented numerals became insignificant as the complexity of the observer's task increased. Table 46, extracted from Gibney's report, presents studies supporting the basic tenet of his thesis, which is, that in general, for the more complex response task, no significant differences are found between standard arabic and segmented numerals.

While a close examination of Gibney's table reveals some differences (though small or debatable) between task complexity for those studies reporting a significant difference in performance for standard arabic vs. segmented numerals and those studies not reporting a significant difference for the same comparison, it does not account for differences in methodologies or consider shifts across comparisons in performance measurements. Cross-study methodological inconsistencies must severely limit any conclusion determined by an examination of such collective results, and the present authors, therefore, are not willing to agree with Gibney. Gibney, seemingly ignoring these limitations, concluded, "--- no appreciable decrement in functional legibility is to be expected from segmented numerals in applied situations where tasks are typically complex".

He tempers his statement with a mention of the possibility that this phenomenon may be, in some respects, a statistical artifact. This seems a reasonable assumption since as response task complexity increases there are more opportunities for variability to enter into the measurement which is not directly linked to legibility factors. As the within groups' variability increases with the more complex response task, statistical tests lose the power to show significant differences between the two display groups.

In Gibney's review a recommendation is made which is well stated and should be headed by all display researchers intent upon accurately defining standards of legibility for their systems applications. "At present, little is known about how these variables influence legibility. Future research on legibility should be conducted under conditions which most nearly simulate the situation for which the proposed design is intended". The present authors heartily agree with the above statement. However, before further conclusions may be drawn about Gibney's central thesis on task complexity and legibility, much additional research data will have to be reviewed and analyzed.

Table 46. The Trend to Significant Differences Between Standard and Segmented Numeral Designs as a Function of Operator Task Complexity. (Ref. 138)

Authors	Instructions	Stimuli	Dependent Variables	Differences
Kershner & Avery, (Ref. 384)	Read messages & use that information to write answers to questions presented for each message.	Numbers, words & abbreviations shown on printers.	Response time, errors.	Not significant.
Fried, (Ref. 383)	Press ready button. Read & write number.	4-digit numbers shown on counters.	Errors.	Not significant.
Alluisi & Martin, (Ref. 382)	Press one of 10 finger keys corresponding to number seen.	1-digit numbers projected on screen.	Response time, errors.	Not significant; segmented "slightly better".
	Press ready button, read number orally.			Not significant.
Fried, (Ref. 383)	Press ready button, read number orally. Press react button.	4-digit numbers shown on counters.	Response time.	p< .05
Cohen & Webb, (Ref. 381)	Pick card from top of stack, read number orally. Place card on 2nd stack.	2-digit numbers printed on cards.	Response time, errors.	p< .01
Reinwald, (Ref. 380)	Read number orally.	1-digit numbers & letters printed on cards.	Threshold distance (psychophysical method of limits).	p< .01
Buschow, K.L., (Ref. 379)	Read number orally.	6-digit numbers on counters Tachistoscopic presentation.	Errors.	p< .001

Conclusion

For CRT display design considerations of matrix formed alphanumerics, it may be concluded that (1) slanted symbols and elongated dot matrices be avoided; (2) that dot matrices be considered as good or better than stroke generated symbols; (3) that a 7 x 9 dot matrix be considered better than a 5 x 7 and, (4) that apparently (limited study) 7 x 9 dot matrix symbols subtending as small as 7 minutes of arc are highly legible.

Solid State Matrix Symbols

This division of the Matrix Symbol Generation Techniques Section addresses the legibility of solid state matrix displays. The variables influencing matrix solid state display legibility essentially are counterparts of similar variables influencing CRT display legibility. This is primarily due to the common elements which ultimately determine the resolution features of the display such as the number of vertical and horizontal resolution elements, emitter size and emitter density.

Although the resolvable elements may be similar, Stenson (Ref. 377), in a review of human factors considerations of alphanumerics for EL displays, reports a study by McLean and Miller (Ref. 378) which indicates that EL displays may not bear the same readability relationships to these variables as do conventional displays. For a more comprehensive description and analysis of the resolution components of solid state displays, see the report section addressing display system resolution.

The following selected studies present legibility information which applies to solid state matrix formed alphanumeric characters.

From tests conducted at Radio Corporation of America in 1960 (Ref. 24), Stephenson and Schiffler (Ref. 323) report, without supporting information, that a 38-segment electroluminescent (EL) display represented a significant increase in performance over a 14-segment design. Five years later at the Rome Air Development Center, Levy and Russo (Ref. 215) reported that a 23-segment font is "generally acknowledged" to be superior when compared with fonts of fewer segments, yet they offer no empirical support for their claim. Stephenson and Schiffler (Ref. 323) responsed to the implications of these reports and designed a study to test the legibility of five representative EL matrices of varying segment numbers.

Segment fonts of 16, 17, 23, 27 and 38 elements were studied (see Figures 76, 77, 78, 79 and 80). Table 47 presents the characteristics of these segmented symbols. The legibility of these five fonts was measured at three visual angles: 10,

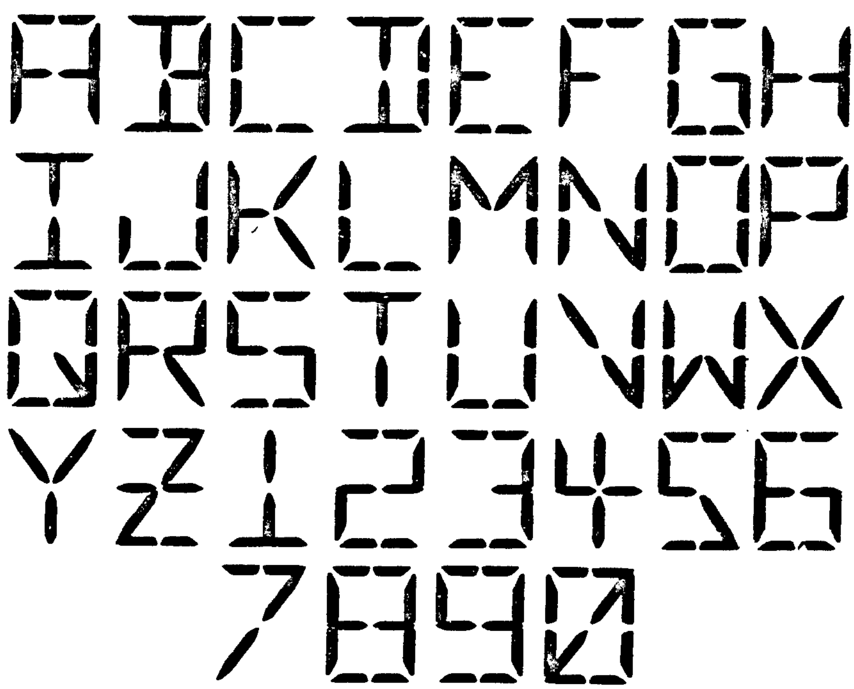


Figure 76. Sixteen Segment Alphanumerics.

Figure 77. Seventeen Segment Alphanumerics.

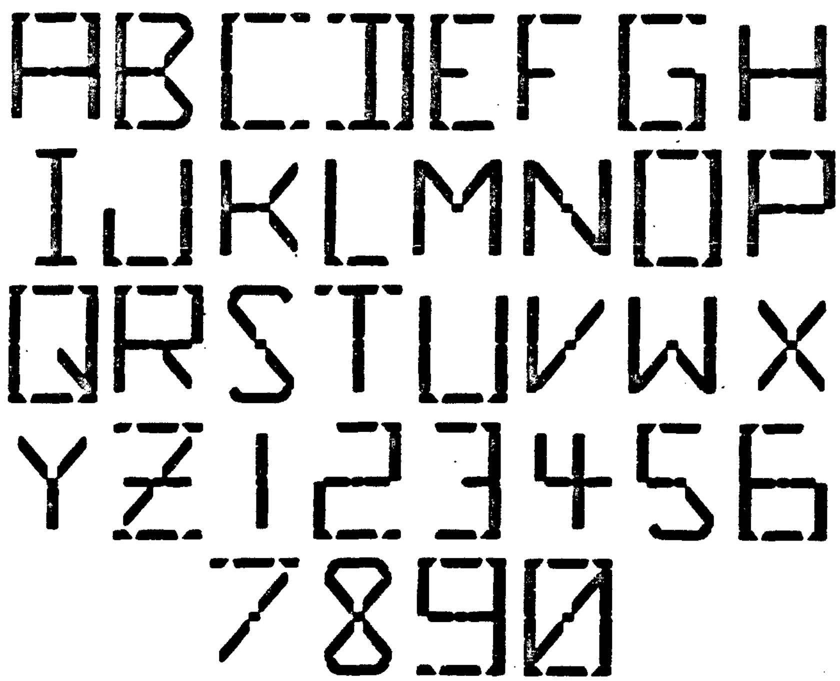


Figure 78. Twenty-three Segment Alphanumerics.

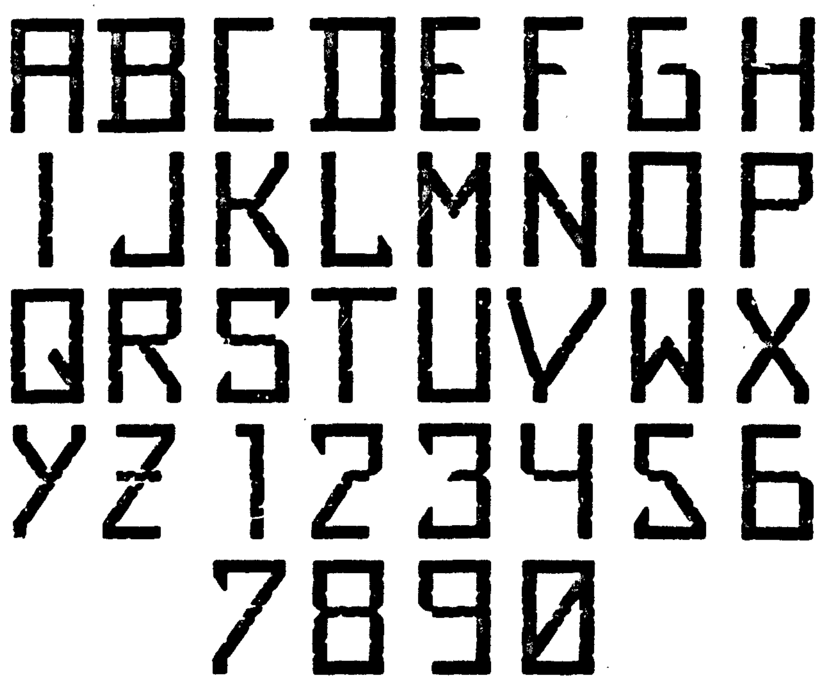


Figure 79. Twenty-seven Segment Alphanumerics.

Figure 80. Thirty-eight Segment Alphanumerics.

15 and 30 minutes of arc. Four subjects (20/30 visual acuity or better) viewed 26 letters and 10 numbers at an exposure time of .25 seconds with an average symbol luminance of 6.60 Ft. Lamberts and a contrast of 4,614 percent.

For accuracy of identification, an examination of Table 48 indicates that of the five fonts tested, the 16 and 23 segment styles were slightly more legible. As Table 47 indicates, there are, however, numerous factors which may have tended to confound these study results. Variations in font, width-to-height, stroke-width-to-height, slanted vs. vertical symbology and brightness could have been the basic reason for performance differences, rather than the manipulated variable segment number. It is observed, however, that no EL font tested reached an acceptable systems design level of reading accuracy. The highest accuracy of identification obtained was 95.1 percent for the 23 segment font at 30 minutes of visual angle. Reading accuracy must approach 100 percent to be acceptable to systems design, and generally the legibility scores shown in Table 48 ranged in the 80 percent region. It is not possible to predict the relative performances of these fonts when conditions permit reading accuracy to approach 100 percent correct identifications.

A close examination of the error scores tabulated in study confusion matrices indicates that the error scores for the 17, 27 and 38 character sets occurred for a few specific characters. This would suggest that much of the weakness of the seemingly poorer character designs can be attributed to a few poorly designed letters or numerals.

Based on the data and the experimental limitations already cited, Stephenson and Schiffler conclude, "The small advantage for the 16 and 23-segment character is probably of little practical significance. Because of its much lower cost and complexity, however, the 16-segment font must be recommended for future application to EL generated alphanumeric displays."

With this conclusion the present authors are uncertain. Due to the unknown effects of the experimental limitations cited, it is impossible to accurately predict the significance of these findings for design purposes. It is therefore recommended that these data be used only as an indication of a probable legibility trend. Certainly these data stimulate the apparent need for a precise, design-oriented investigation of EL fonts.

King et al. (Ref. 208) recently published a study in which subjects read three-digit numbers from seven-segment electroluminescent readouts. Numeral height and width were 0.40 inches and 0.28 inches respectively. Stroke width of each segment was 0.05 inches. Viewing distance was 28 inches. The objective of the study was to determine legibility and "comfort-level" brightness contrast percentages for the light-emitting displays for

Table 47. Summary of Font Characteristics.

Number of Elements	16	17	23	27	38
Manufacturer	RCA	Stromberg-Carlson	Kearfott	RCA	RCA
Width-to-Height (Percent)	75	66.7	73.3	66.7	62.5
Stroke-Width-to-Height (Percent)	6.25	13.3	6.7	13.3	12.5

Table 48. Percent Correct Response.

Visual Angle	Number of Segments in Font: 16	17	23	27	38	Average
30	90.2	90.9	95.1	88.1	86.8	90.2
15	85.4	79.9	90.9	84.7	84.7	84.9
10	89.5	79.1	84.7	75.6	75.6	80.9
Average	88.3	83.0	90.2	82.8	82.3	85.3

cockpit illumination conditions ranging from zero to 10,000 Ft. Lamberts. King et al. used a legibility criterion requiring correct reading of three series of random three-digit numbers displayed on the seven-segment readouts. They report that, even with minimal contrast, pilots could read the numeric readouts consistently with 100 percent accuracy. They do report, however, that the amount of time required to read the display was significantly greater when the displays were operated at minimum legibility contrast percentages than when the displays were operated at higher contrast percentages judged by the pilots to be "comfortably" bright. Mean reading time at the minimum legibility contrast percentages levels was 2.5 seconds, while mean reading time reduced to 1.2 seconds for the higher "comfort-level" contrast percentages. Each of the above reading times includes approximately 0.5 seconds required for the subjects to depress a hand-held response button.

Conclusion

At this time it is not possible to specify with any degree of certainty the optimum solid state matrix alphanumeric configuration. The study by Stephenson and Schiffler (Ref. 323) leads us to conclude that simply enlarging the number of segments composing EL symbols does not necessarily result in improved accuracy of identification. Also, it is noted that most of the errors recorded were for a few poorly designed letters or numerals which would suggest selective redesign of the characters to improve legibility. Finally, the study by King et al. (Ref. 208) suggests that seven-segment EL numeric readouts when read 100 percent correctly require 1.2 seconds viewing time (including 0.5 second required to depress a hand-held response button) when characters are read at high "comfort-level contrast percentages."

RESEARCH REQUIREMENTS

Introduction

While it is known that over half the experimental investigations of symbology deal with some aspect of alphanumerics, it is readily apparent from an examination of the previous technical section that further research is required to adequately define legibility requirements for alphanumeric symbology used in an electronic display context. This applies to CRTs incorporating both raster and caliographic presentation techniques and to solid state matrices such as electroluminescent displays. While some variables affecting legibility logically apply to all electronic symbol generation techniques such as symbol height and width-to-height, some variables are peculiar to the particular generation technique used such as emitter size for solid

state symbology. In any case, all alphanumerics for electronic display application should be directly concerned with the legibility of capital letters, numerals or words. Only objective studies requiring visually screened subjects to actually identify symbols or words under controlled conditions should be conducted. These should be used in lieu of studies incorporating a subjective or judgemental methodology which does not produce numerical data relating to the viewers ability to identify symbols or read words. Subjective evaluations, however, may be used to determine subject preferences and these data then may be related to objectively determined performance data.

Many past alphanumeric legibility studies have incorporated extremely fast exposure times or dim illumination levels to introduce large error scores which can be analyzed and compared statistically. The rationale for doing this is based on the assumption that an alphanumeric configuration which performs well under these conditions will also perform better under operational conditions. As previously pointed out, however, this has not always held true. Consequently, for purposes of increasing error scores or stressing the subject in legibility studies, it is recommended that an increased workload be imposed on the subjects. Under these circumstances, viewing times can then be studied as the subject controlled latency from symbol exposure to symbol identification. Likewise, illumination levels can be raised to reflect the operational range encountered in the environment. This approach to viewing time and higher illumination levels will undoubtedly reduce error scores, perhaps to zero. If this occurs, then accuracy of identification will approach 100 percent (the only operationally acceptable level) and the analysis would consist of two factors: (1) the statistical differences in speed or rate of symbol identification and (2) the use of confusion matrices. The use of confusion matrices would allow individual analysis of the symbols both for speed or rate and accuracy (if any errors occur). This would eliminate difficulties in interpreting the relative superiorities of alphanumerics which arise from the averaging of performance across all symbols. When performance deficiencies for individual symbols are established, then design manipulation of the characteristics of those individual symbols to improve performance would be feasible. This would eliminate much inefficiency involved in developing whole new sets of alphanumerics instead of simply improving problem symbols existing in an already proven set.

The total number of design variables which must be considered in generating design-oriented, generalizable legibility data is quite large. The effects of combinations of variables, variable interactions and ranges of variables are critical in producing design-oriented data. While much of the research in alphanumerics is at the applied level and developed primarily to answer specific questions, researchers should make every attempt to study legibility as effected by all relevant factors.

Factors under research consideration should be systematically studied throughout their entire ranges and not just at selected values determined by a specific usage. Ultimately, researchers should attempt to develop general principles of symbol legibility rather than just answering specific questions raised by a particular application.

The following research requirements are based on electronically generated capital letters and numbers which are directly viewed by visually screened subjects at a 28-inch viewing distance.

As many of the variables listed in Table 49 as possible should be investigated across as much of the specified range of these variables as is feasible. In instances where this cannot be done, each of these variables should be quantified and rigorously controlled as an independent variable in the research. This approach is necessary because of the large number of interactive variables influencing alphanumeric legibility.

Font or Style

The applicability of non-CRT research to a CRT operational situation is complicated by the variations in alphanumeric legibility induced by the method of symbol generation and display media. In the face of the large amount of non-CRT font work already completed, it is recommended that further font research for electronic display devices be conducted specifically on CRTs. The non-CRT and CRT fonts found to be generally superior are listed in Table 49. Cross comparisons (using recommended performance measures and analysis procedures) of these fonts across the other conditions in Table 49 would be useful in establishing which one is generally superior to the others. Subsequent CRT font research could then be conducted to improve any problem symbols existing in the best of these fonts until ultimately a single most acceptable CRT font is developed. This font could then be standardized for electronically generated alphanumeric symbology with a broad base of empirically established data for effective design considerations. For research recommendations on other than alphanumeric symbols, see section on information coding.

Symbol Size and Proportion

Usable electronic display research on symbol size and proportion is virtually a data void with the exception of some recent work conducted by the Mitre Corporation. To rectify this data void the symbol size and proportion figures for the non-electronic display alphanumeric research reported have been examined to determine those values which might best serve to establish basic research requirements for electronic displays. It is therefore recommended that a symbol height of 10 to 30 minutes of visual angle, symbol widths of 30 to 110 percent of

Table 49. Research Recommendations: A Summary.

VARIABLE	VARIABLE RANGE
Font	Mackworth Lincoln/Mitre Leroy Mil-M-18012 Landsdell Foley/Landsdell
Symbol Height	10 to 30 minutes of arc
Symbol-Width-to-Height	30 to 110 percent
Symbol-Stroke-Width-to-Height	5 to 30 percent
Brightness	
Panel Mounted Displays	.1 to 1,000 Ft. Lamberts
Head-Up Displays	.1 to 8,000 Ft. Lamberts
Resolution	
Active scan lines per	
Symbol Height	10 (minimum)
Raster Lines	525 and 945 line systems (others as appropriate or available)
Bandwidth	1 to 20 megacycles
Symbol Spacing	5 to 100 percent of symbol height
Viewing Angle	Establish the angle off of direct viewing which produces a significant decrease in legibility in terms of both speed and accuracy of identification.
Edge (Off-Center of Tube) Displayed Symbology	Horizontal, vertical and oblique displacements, 0 to 100 percent from the center in 10 percent intervals.

height and symbol stroke widths of 5 to 30 percent of height be investigated on CRTs for as many of the variables in Table 49 as is possible and across as much of the variable range indicated as is feasible.

Symbol Spacing

Symbol spacing refers to the space or interval between adjacent symbols expressed as a percentage of symbol height. Symbol spacing from 4.8 to 63.2 percent have been reported for non-electronic display studies with limited conditions of brightness and symbol size. It is therefore recommended that a more comprehensive range from 5 to 100 percent be investigated on CRTs across as many of the conditions indicated in Table 49 as is feasible. This will establish a more complete and useful design-oriented data base.

Words

It is recommended that word legibility and alphanumeric symbol legibility be tested under identical experimental conditions on a CRT which is capable of manipulating symbol spacing, resolution and brightness factors. This would enable realistic comparisons of word vs. symbol legibility that could be applied to an operational design situation.

Edge (Off-Center of Tube) Displayed Symbology

Edge displayed symbology refers to symbols viewed at other than the center of a CRT. Very little research has been reported on this subject and that which has does not report the exact position on the CRT where the symbology was viewed. It is therefore recommended that future research begin by first establishing symbol legibility at the center of the tube, then successively moving the symbology peripherally (a specified percentage of the distance from center to edge) to re-establish symbol legibility for each successive step. The legibility data could then be plotted as a function of displacement percentage.

Moreover, it is recommended that 0 to 100 percent horizontal, vertical and oblique displacements from the center be investigated in 10 percent intervals. The symbology viewed should be varied across as many of the conditions in Table 49 as possible.

Viewing Angle

It is recommended that the angle off of the normal viewing angle which produces a significant decrease in legibility in terms of both speed and accuracy of identification be determined for as many of the conditions in Table 49 as possible.

Symbol Blur

Symbol blur ratios from 0.00 (no blur) to 2.0 should be investigated in small increments on CRTs for both accuracy and speed of symbol identification for as many conditions in Table 49 as is technically feasible. Also, careful attention should be given to the analysis of confusion matrices generated from blurred symbol data.

Matrix Symbol Generation Techniques

Cathode Ray Tube Matrix Symbols. It is recommended that further research such as that performed by Vartebedian (Ref. 335) be conducted for a vertically oriented 7 x 9 (others as technically available) dot matrix. This symbol configuration should be tested under variations of luminance, contrast percentage, ambient illumination, symbol height and viewing angle. See Table 49 for approximate ranges of these variables.

Solid State Matrix Symbols. It is recommended that EL displays from 7 to 38 segments with equal width-to-heights and stroke-width-to-heights be tested for speed and accuracy of identification using both gross scores and individual symbol analysis in confusion matrices. All symbols tested should be vertically oriented at a constant brightness and a 28-inch viewing distance. Variations in ambient illumination and contrast percentage should be emphasized in conjunction with identification with and without workload stress.

SECTION VI

SCALE LEGIBILITY CONSIDERATIONS

INTRODUCTION

In a gross sense, displays can be categorized as static or dynamic. Static displays may be considered as those which present the same information over time. Typical examples include signs, markings, labels and maps. Dynamic displays, on the other hand, present information which is subject to changes over time and which is intended to inform the observer of the status, condition or value of a parameter of information such as altitude or airspeed. Obviously, much of the information presented to the pilot involves dynamic displays. This section addresses the readability of dynamic cockpit information displays incorporating scales.

Dynamic displays present information in coded form. In the cockpit, much of the information which is coded for display must be read quantitatively, and the manner in which such information is coded can have a marked influence upon quantitative display reading times and accuracies.

In their review of electrically and optically generated displays, Ketchel and Jenney (Ref. 206) have indicated that electronic flight displays may contain examples of practically every type of information coding technique commonly used today in electromechanical instruments. It would appear, therefore, that all of the "old" scale reading problems will exist in electronically generated flight displays, and that the old problems may be complemented by some new problems which are directly related to the new display medium.

The objective of this section is to identify, discuss and present experimental data on the influences of the following research and scale design factors upon the pilot's ability to perform quantitative instrument reading tasks:

- Considerations of Display Integration
- Considerations of Research Methodology
- Mission-Imposed Scale Reading Accuracy Requirements
- Scale Shape (Circular, Vertical or Horizontal)
- Non-Linearity of Scales
- Numbering Scale Interval Values
- Scale-to-Readline Distance
- Stroke Width of Scale Markings
- Subdividing Major Scale Intervals
- Scale Interpolation
- Checkreading Cues

The impact of the design factors listed above are not unique to electronically generated flight displays. Indeed, none of the experimental literature which was reviewed in relation to these design factors was generated in an electronic display context. Nonetheless, these factors, and more, must be considered in designing electronically generated flight displays. Furthermore, a critical review of the available literature indicates that data regarding the impact of these design factors are not as consistent and conclusisive as many authors seem to imply. Finally, there appears to be sufficient evidence to warrant caution in unquestioned application of some research findings generated in the context of the "printed medium" to the electronic display medium. A review of existing data is a necessary prerequisite for identifying necessary research requirements for electronic displays.

Finally, the reader will note that the effects of vibration and g-force upon scale reading are not contained in the above listing. Data on the impact of these variables upon display reading will be found in the report section dealing with environmental factors. The reader also will note that important electronic display-related factors such as contrast ratio, vertical resolution and bandwidth are not contained in the above listing. Data on these considerations are found in report sections dealing with contrast and resolution requirements respectively. For dynamic displays based solely upon numeric readouts, the reader is referred to the report section dealing with alphanumerics. For qualitative "on versus off" indications, the reader is referred to the section dealing with information coding.

CONSIDERATIONS OF DISPLAY INTEGRATION

Numerous features under the control of the display designer can impact upon the ability of the pilot to extract quantitative information from straight or circularly scaled dynamic displays. Although admittedly an over-simplification, controllable design features may be categorized into one of two fundamental classes: (a) single-thread design features, such as scale factor or number of graduation marks, which influence the observer's ability to read even the most simple and straight-forward display types; and (b) factors of display format and interaction, such as the use of multiple scales, multiple pointers or combinations of scales and readouts into an integrated display of related information.

Legitimately, single-thread features cannot be considered independently in predicting the total usefulness of a particular display design. For example, numerous studies comparing alternative designs of either round dial or vertical scale

altimeters have found statistically significant and operationally practical differences in display reading time and reading errors among displays which were similar in size, scale factor, number of scale graduation marks and the range of altitude displayed. Simon and Roscoe (Ref. 308) also have shown that properly combining separate items of scaled information (vertical velocity, barometric altitude and command altitude) into a single integrated display can result in improved pilot decision making performance.

Many factors other than those discussed subsequently in this section influence the final usefulness of any display design. Although single-thread scale design recommendations are referenced in subsequent pages, the reader will not find a comprehensive review and analysis of studies which emphasize display format or integration. The authors are aware of the vital importance of these factors. However, we also are aware that no magic exists in the integration of various parameters; any single parameter cannot be read more accurately in an integrated display than it could be read as a separate display, at least in terms of proper single-thread scale design considerations. Furthermore, within the context of cockpit displays, practically all research relating to scale design has been conducted within the constraints of electromechanical display design. It would appear that many display format and integration problems associated with electromechanical designs need not be present in electronic flight data displays because of the seemingly limitless design flexibilities which this medium offers. Additionally, even a cursory review of the proliferation of electronically generated flight display formats indicates that at least some display designers have successfully conceived of entirely novel horizons in display formats and, most likely, in human performance problems induced by the new formats for which no design guidelines exist.

The technical content of this section, therefore, does not address the important factor of display integration. Rather, it emphasizes scale design variables which are most directly associated with accuracy and reading times for individual quantitative scales.

CONSIDERATIONS OF RESEARCH METHODOLOGY

Not all data are good data. Subsequent pages within this section review display legibility research with the objective of drawing objectively-based conclusions regarding scale design for electronic flight displays. Certain constraints were placed upon the selection and interpretation of the human performance data which are presented below, and further restrictions must be placed upon generalizing the design criteria directly to

electronic flight display application. The constraints arise primarily from aspects of the methodologies of the research which was reviewed. Obviously, studies were not considered when experimental control of relevant variables was not apparent. Beyond this, however, four additional methodological considerations bear directly upon the generalization of past research findings to electronic flight display design, or for that matter, to electromechanical display design.

Of primary concern for the design of electronic flight displays is the fact that, during the last quarter of a century, all of the scale design research which was identified and reviewed was performed within the context of electromechanical indicators. Although it may be anticipated that many of the design principles and guidelines developed for electromechanical instruments should apply equally well to electronic displays, a degree of conservatism is warranted in unquestioned generalization of scale design findings which may be significantly effected by the electronic display medium. Of particular concern are the effects which number of active raster lines, bandwidth, read-line configuration, edge gradients and contrast ratio variations may have upon the pilot's ability to identify and discriminate among or interpolate between minor graduation marks of the sizes generally recommended for printed dial faces. Unfortunately, no clearly definitive studies were found which examined these variables in line written or raster display contexts. A review of considerable amounts of other human performance data, however, indicates that very real problems may exist in the area of scale legibility on electronic flight displays if current human factors standards are applied directly. This topic is discussed further under research recommendations.

A second methodological consideration is the amount of time which subjects spent viewing each experimental scale design in the studies which were reviewed. In order to induce "stress" and reading errors into experimental situations, numerous researchers have carefully and systematically controlled display viewing time to periods as brief as 75 milliseconds (Refs. 66 and 67). Studies of pilot eye fixations during instrument flight (e.g., Refs. 121, 125, 139 and 140), on the other hand, have consistently shown that the durations of eye fixations on a variety of types and kinds of flight instruments ranging from 1950 vintage displays through current Air Force integrated instruments vary from approximately 300 to 700 milliseconds. Serious questions arise not only regarding the face validity of studies using such brief exposure time, but also regarding the predictive validity and, therefore, the design utility of results produced by such studies.

In two classic experiments, Christensen (Refs. 66 and 67) compared instrument reading performance at five different viewing times (75, 150, 300, 600 and 1,200 milliseconds). Aside from showing that probability of misreading the instruments

decreased markedly as viewing time increased, he also vividly demonstrated that relationships discovered at one viewing time became insignificant and even reversed at other viewing times. This trend was particularly pronounced in the moving pointer versus moving scale comparisons. For exposures up to and including 300 milliseconds, mean probability of display reading error was approximately 8% less for the moving scale display. However, at and above 600 milliseconds, mean reading error was approximately 5% greater for the moving scale display. The interaction of display type reading time was statistically significant at the .01 level. Similar reversals also have been reported by Elkin (Ref. 115), and studies by Grether (Ref. 148), Coonan and Klemmer (Ref. 89) and Thomas (Ref. 329) provide evidence of such an effect. As Christensen points out (Ref. 66), the use of brief exposure times as a means of inducing display reading errors so that statistically reliable differences may be established among dials gives rise to grave questions regarding the validity of such results. From a design standpoint, it also is apparent that short exposure data cannot be generalized to longer duration cases.

A third methodological consideration involves the amount of time which experimental subjects spent reading experimental scales in studies where display viewing time was not directly controlled as an experimental variable. In this type of study, experimental subjects were allowed as much viewing time as they needed to accurately read each display, with reading time typically having been recorded as a measure of operator performance.

Senders and Cohen (Refs. 82 and 296) and Hake and Garner (Ref. 154) were among the first to consider that the amounts of time which subjects required to read instruments in laboratory experiments were frequently much longer than pilot eye fixation times recorded in simulated or actual flight settings. Studies are reported, in fact, in which experimental reading times have been as much as 10 times as great as pilot eye fixation times (Ref. 202). Senders and Cohen (Ref. 296) make the following comment regarding this type of observation: "A pilot who has

> been flying a level course for the past hour has less to learn from his altimeter than would an observer brought into the situation "cold", and his reading might be expected to be correspondingly faster. ---Unlike the pilot, the subject in the laboratory experiment, where settings are presented randomly, makes independent judgements on each trial.--- It should be clear from the above that more stimulus information is presented to the subject in an experiment than to the pilot. It is not surprising, therefore, that the times required for instrument reading are much greater in the experimental situation than in the operational one."

To test their hypothesis, Senders and Cohen (Ref. 296) conducted a study in which seven groups of 20 subjects each read horizontal straight scales. Two groups read random display values (rectangular probability distribution), while the remaining groups received a conditional probability of displayed values. Under the conditional probability distributions, displayed scale values remained unchanged for a series of ten experimental trials. Display reading errors were converted to information transferred in bits, with the maximum possible information transfer having been calculated as 3.32 bits. Their results clearly showed that information transferred was consistently greater for the groups using the conditional probability distribution. This effect was apparent at both 225 and 775 millisecond viewing times, with the conditional probability group mean performance having been .15 to .20 bits better.

What do the findings of Senders and Cohen mean to the interpretation of the scale legibility literature? Their findings indicate that results of studies in which reading times are experimentally controlled may not be directly useful in predicting precise operational performance levels, even though the experimentally controlled exposure times may correspond directly with empirically determined pilot eye fixation times. This follows since practically all scale legibility studies have employed random (non-conditional) probability distributions of displayed scale values. Furthermore, there are no published studies which provide unequivocal guidelines for relating scale reading accuracy at particular experimentally controlled exposure times to operational scale reading accuracies at typical pilot eye fixation times. On the other extreme, it can be argued that, if a precise quantitative reading must be made from a scale, the pilot will devote as much time as necessary to reading the instrument. One must ask, however, how much time a pilot can reasonably devote to each display from which he wishes to make a reading of pre-specified accuracy? In other words, one must question the rate of information transfer. In this regard, it would appear that considerable caution must be applied in over generalizing from studies in which display reading times have been as great as four to six seconds in duration.

In light of the above methodological considerations, and the impact which research methodology has upon scale legibility findings, research studies reviewed below were limited to those which employed display reading times of at least 500 milliseconds. Additional scale reading considerations related to both research methodology and the utility of state-of-the-art guidelines for the design of quantitative dynamic information displays employing electronic display media are discussed under research recommendations.

An additional factor in assessing the quality of existing research involves viewing distance. Not all scale reading studies have incorporated an approximately 28-inch viewing

distance between the observer's eyes and the experimental displays. Indeed, some researchers have employed viewing distances ranging up to 20 feet in order to accommodate a large number of subjects into a "mass viewing" situation. This expedient appears to have been used in cases where more sophisticated laboratory devices, such as tachistoscopes, were not available, or where large numbers of subjects have been involved. In cases where viewing distances have been exceptionally large, sizes of stimulus materials (i.e., experimental displays) were increased proportionately so that the visual angle subtended by the stimuli at the eye would approximate the angle which such displays would subtend at a cockpit viewing distance of approximately 28 inches.

One must question this type of expedient and ask whether data from studies employing exaggerated viewing distances apply to shorter viewing distance situations in which the visual angle of the stimuli is held constant. The apparent answer to this question is that relationships found at one viewing distance may totally change at another viewing distance.

Churchill (Ref. 69) investigated the accuracy of interpolating between vertical scale graduation marks as a function of the distance between graduation modes. Interpolation accuracy also was determined for viewing distance of 28, 56 and 84 inches. For the latter conditions, display size was varied in order to hold visual angle constant. Results showed that interpolation error decreased with increasing visual angle for the 28-inch viewing condition, was relatively unaffected by visual angle for the 56-inch viewing distance, and increased with larger visual angles for the 84-inch viewing distance. The visual angles involved ranged from one to three degrees. In a similar type of investigation, Chapanis and Scarpa (Ref. 64) investigated the ability of subjects to read a round dial display to the nearest digit. A 2.8-inch dial was used as the reference size. The dial was read at viewing distances ranging from 14 to 224 inches. Size of the dial was varied in proportion to viewing distance to hold the visual angle correlates of dial size constant at 5^{o} 21'. Results showed that reading time became significantly shorter for viewing distances greater than 28 inches. Although not statistically significant, frequency of readings in error decreased sharply for viewing distances greater than 28 inches. Interestingly, results of these two studies also tend to indicate that 28 inches, the assumed "standard cockpit viewing distance" employed in the majority of instrument legibility research, may not be an optimum viewing distance in terms of either reading times or error rates. From a design standpoint, it is apparent that data taken at other than operationally specified viewing distances may not be generalized without caution to other viewing distances.

A final word. Human performance data which are discussed below reflect only the pilot's task of reading displayed values.

Performance of the human operator as a continuous controller are not directly addressed.

It has long been recognized that both stability and precision of continuous control tasks are significantly affected by display scale factor variables. As Roscoe (Ref. 282) points out, for continuous control tasks, display scale factor is a serious problem because performance deteriorates as scale factor changes in either direction from some optimum value. In general, as scale factor is reduced, precision of control deteriorates, but stability improves. As scale factor is increased, precision improves at the expense of increased pilot workload up to a point where the system becomes unstable and "the task blows up in your face."

The data presented below only reflect display reading and do not address the effects of scale factor upon continuous control task performance. Continuous control performance is a function of many interacting variables including display dynamics, controller dynamics and total system dynamics. If one wishes to assume that a parameter can be controlled, at best, only to the degree of precision with which it can be read from a display, then the data which follow may be useful in predicting precision of control. If, however, there is any question regarding the degree to which system stability may be sacrificed, then system performance requirements may have to be re-assessed, or system stability experimentally varified using man-in-the-loop or computer simulation techniques.

The intent of this section has not been to bore the reader with the many seemingly academic aspects of display research. Rather, our objective has been to review the critical aspects of display research which frequently are overlooked even today. The intent of the review is three-fold: (1) to attempt to develop a basis for understanding at least some of the numerous inconsistent and contradictory data which have been published over the past quarter of a century; (2) to provide criteria for selecting display legibility research data for use in this report; and (3) to provide at least a brief overview of salient methodological consideration for future research.

MISSION-IMPOSED SCALE READING ACCURACY REQUIREMENTS

In designing dynamic displays for optimum quantitative readability, the display designer must first specify the degree of precision to which each parameter must be read or controlled. Obviously, if heading must be read or controlled to within 0.5 degrees in order to satisfy mission requirements, then providing a display of heading which can be read only to a five degree accuracy is insufficient. Conversely, providing a display with

which heading could be read to a .01 degree accuracy does not imply that the display is now "better" than required. This follows for several reasons. First, when the precision of display readability tends to exceed sensor or computer accuracies, minor fluctuations in displayed values may only reflect sensor-processor-display noise, and there is no known value in displaying any type of visual noise. As will be shown subsequently, display scales for highly precise readings frequently require increased reading time. It must also be remembered that scales designed for maximum static legibility may become highly unreadable under dynamic situations where displayed values are subject to rapid changes at relatively high rates. Finally, designing scales for highly precise readability may require exceedingly larger or long scales, only a small portion of which may be displayed at any given moment.

Much of the human factors research which has been directed toward scale readability has been directed toward minimizing scale reading and interpolation errors. However, it is not always a display scale design objective to minimize scale reading error. Rather, many scales must be designed only to result in pre-specified, selected accuracies. Therefore, many of the data which follow are presented with the objective of showing the relationship between selected designer-controlled scale design variables and indices of operator performance such as magnitude of reading error, probability of occurrences selected error magnitudes, and time required to make display readings. The designer may then select the design characteristics which will satisfy known reading accuracy requirements.

The construction of any scale designed to be read quantitatively must begin with a specification of the accuracy to which the scale must be read. It has long been recognized that all parameters which may be displayed in the cockpit, and consequently may appear on an electronic display, must not necessarily be read or controlled to the same degree of precision. Indeed, the degrees of precision to which different flight data parameters must be controlled has been the topic of more debate than research and certainly is influenced by unique aircraft dynamics and mission considerations. In our attempt to provide some starting point, however, selected data collected by Williams (Ref. 359) are presented in Table 50. Williams indicates that the basic data, some of which have been summarized in the table, were compiled from many sources including flight handbooks, interviews with military and industrial pilots, manufacturer-supplied data, and other applicable publications. He attempted to collect data which were representative of jet powered fixed-wing aircraft, V/STOL aircraft of several configurations, and rotary wing aircraft. The data are reported to have been derived within the context of consideration of the following mission segments: Takeoff, climbout, cruise, transition to or from cruise, transition to or from vertical flight, approach to landing, hover, landing (including carrier),

Table 50. Maximum Ranges, Rates of Change and Accuracies Associated with the Control of Selected Flight Data Parameters. (Adapted from Williams, Ref. 359)

Parameters	Maximum Range To Be Displayed	Maximum Rate of Change of Parameters	Maximum Degree of Normal Accuracy Required
Load Factor (G)	-4.5 to +10g	2g/second	±.2g
True Airspeed	-30 to +500 knots	45 knots/second	±1 knot or 1%
Lateral Airspeed	-30 to +30 knots	20 knots/second	±2 knots or 3%
Pressure Altitude	-1,000 +80,000 feet	20,000 feet/minute	±10 feet or 0.5%
Absolute Altitude	0 to 5,000 feet	Subject to terrain	±2 feet or 5%
Angle of Attack	-5 to +30 degrees	60 degrees/second	±0.25 degrees
Angle of Sideslip	-40 to +40 degrees	60 degrees/second	±1 degree or 10%
Flight Path Angle	-180 to +180 degrees	60 degrees/second	±0.25 degrees
Heading Angle	0 to 360 degrees	50 degrees/second	±0.75 degrees
Pitch Angle	-10 to +15 degrees	2 degrees/second	±0.5 degrees
Roll Angle	-180 to +180 degrees	200 degrees/second	±0.5 degrees or 5%
Takeoff Distance (Ground Roll to Clear 50 ft. Obstacle)	0 to 9,000 feet	200 feet/second	±5 feet
Vertical Velocity	-20,000 feet/minute to +20,000 feet/minute	6g	±20 feet/minute or 0.5%

antisubmarine warfare sonar drop or trail, air to ground rocket delivery, and loft bombing. It must be pointed out that the data in Table 50 represents only the most demanding display reading conditions identified by Williams and do not represent the totality of the data which he developed. However, similar analytically derived data by Murphy et al. (Ref. 252) are in close agreement.

SCALE SHAPE

Before directly addressing data which bear directly to scale design, it must be pointed out that the effect of scale design variables such as scale factor and number of graduation marks upon quantitative reading performance may not be identical for circular and straight scaled displays. Furthermore, reading accuracies and times may be influenced by display design factors such as the use of multiple pointers, multiple scales and a reliance upon digital readouts of portions of the displayed information. Several methodologically sound studies which have systematically examined the effect of scale shape in controlled experimental situations are reviewed below.

Using printed booklets containing reproductions of nine different designs for altimeters, Grether (Ref. 149) investigated speed and accuracy in a display reading task in which exact values were displayed and interpolation was not required. The displays which Grether used are shown in Figure 81 along with display interpretation times and the probability of occurrence of reading errors in excess of 1,000 feet. Additionally, Table 51 shows total frequency of reading errors as well as reading errors in excess of 100 feet.

Of the display scale designs which Grether studied, data from designs D, G, H and I appear most directly applicable to electronic flight displays. This follows since none of these particular designs incorporate multiple pointers or multiple scales, which were solutions to the unique electromechanical design problem of displaying a large range of the parameter in a fixed and relatively small display area. Excluding the numeric readout which always resulted in very few errors, it can be seen from Table 51 and Figure 81 that display G consistently ranked lowest in terms of reading error. Displays D and H rank either second or third depending upon the error data upon which the rankings are made. In terms of interpretation time, however, display G ranked last, with a mean interpretation time of 2.3 seconds. Display D and H were identical at 1.7 seconds. One conclusion is that displays which are most accurately read may require greater reading times. This finding is not unique to Grether's study.

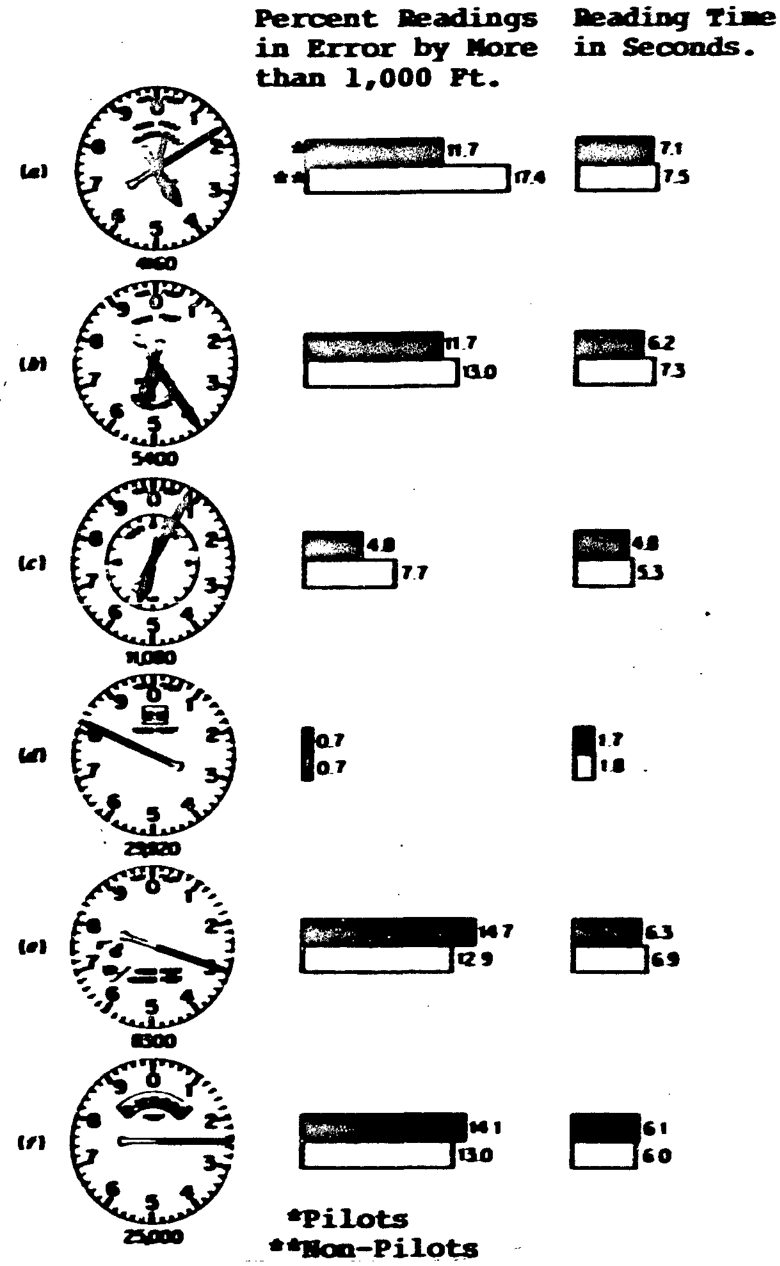


Figure 81. Reading Errors and Interpretation Times for Selected Altimeter Designs. (Adapted from Grether, Ref. 149)

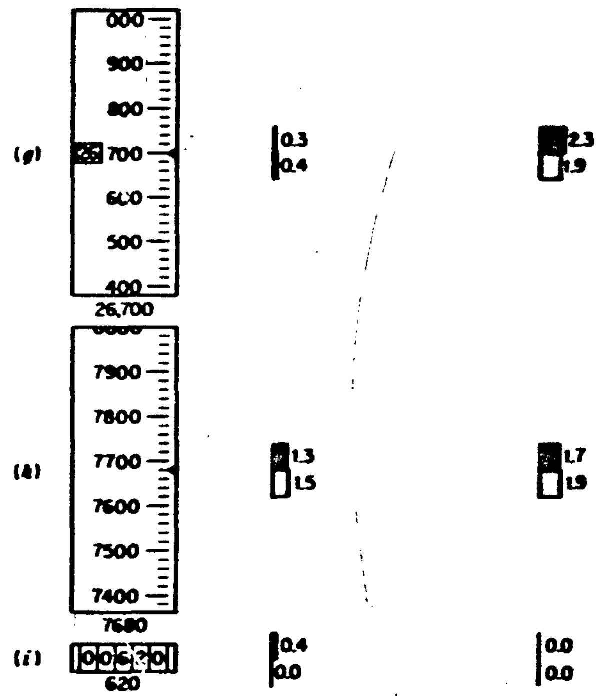


Figure 81 — (Continued)

Table 51. Frequency of Errors and Interpretation Times for 97 Pilots Reading Altitude from Nine Experimental Displays. (Adapted from Grether, Ref. 149)

Experimental Display Designs*	Percent Errors			Mean Interpretation Time in Seconds
	Total	100+	1,000+	
A	15.9	13.1	11.7	7.1
B	15.0	12.6	11.7	6.1
C	8.3	5.5	4.8	4.8
D	3.5	0.9	0.7	1.7
E	17.3	15.0	14.5	6.3
F	24.1	22.0	14.1	6.2
G	2.1	0.5	0.3	2.3
H	2.5	1.7	1.3	1.7
I	0.6	0.6	0.4	0.0

100+ Reading errors greater than 100 feet of altitude.
1,000+ Reading errors greater than 1,000 feet of altitude.
*See Figure 81 for example of each display type.

In a similar type of study, Elkin (Ref. 115) used a tachistoscope to control display reading time, and experimentally compared a circular dial, vertical scale, and an open window scale which was similar to the vertical scale, but incorporated a display aperture which exposed only approximately one inch of the scale. Two display reading times are of interest. They are 1,080 milliseconds, and subject-terminated reading times. Under experimental conditions comparable of those used by Grether (Ref. 148) in which no interpolation was required, data from Elkin's study are shown in Table 52 for conditions in which displays scaled to five unit increments were read to five unit increments, and displays scaled to one unit increments were read to one unit increments. In terms of display reading time under the subject-terminated conditions, reading times were quite comparable for each display type, although consistently more time was required to make one-unit readings for either display type. In terms of percent of readings in error, the vertical scale was consistently poorer. However, under subject-terminated conditions, the open window display was superior to the circular display, while the opposite was true under the 1,080 millisecond viewing time conditions. No reason for the reversal is apparent, nor was it reported whether the differences are statistically significant. It is also of interest to note that the error rate data reported by Elkin are considerably greater than those reported by Grether, possibly because Elkin stressed quick display reading to his subjects.

Similarly, Graham (Ref. 144) compared vertical and horizontal linear scales with a round-dial display. Display viewing time was one-half second, and all experimental subjects received training in the display reading task prior to the experimental trials. No interpolation was required in reading the displays. Results showed that overall reading errors were greatest for the vertical scale, with the circular scale having been second best. The horizontal scale produced the fewest errors.

Of greater interest, however, is the fact that Graham also measured reading error as a function of pointer position along each scale. Because he simulated moving pointer displays, and anticipated that subject eye fixations prior to each dial reading trial might tend to be in the center of the scale, his data also provide for an examination of reading errors as a function of the deviation of the pointer from the center of each scale range. Consequently, Graham has provided information which may be directly applicable to moving scale displays in which the readline is fixed, and the pilot fixates in the immediate area of the readline in order to make scale readings.

Graham reports that the interaction of scale shape by pointer position was statistically significant (P = .001), indicating that the position of the pointer along the scale has more effect upon accuracy of reading one type of scale than upon another. Considering just the center 20 percent of the

Table 52. Time and Error Scores for Open Window, Circular and Vertical Scales. (Adapted from Elkin, Ref. 115)

		Display Complexity			
		Scaled at five unit intervals and read to five unit increments.		Scaled on one unit intervals and read to one unit increments.	
		RT	%E	RT	%E
Subject-Terminated	OW	1.02	0.85	1.21	0.00
	C	1.13	2.50	1.47	2.50
	V	1.18	3.35	1.49	3.35
1,080 Milli-second Viewing Time	OW	NA	2.10	NA	2.10
	C	NA	1.25	NA	0.85
	V	NA	2.50	NA	2.90

RT - Display reading time in seconds for subject-terminated conditions.

%E - Mean percent of display readings which were in error.

NA - Not applicable.

OW - Open Window display.

C - Circular display.

V - Vertical display.

vertical and horizontal linear scales, no appreciable difference in reading error was apparent. Also, performance in the center 20 percent of either linear scale was not appreciably different from performance on any comparable portion of the round dial display. Expanding the comparison interval to include the central 60% of the linear scales, the horizontal and round dial displays produced comparable performance, but errors were approximately 70 percent greater for the vertical scale.

Results of Graham's study appear to conform in part with Sleight's (Ref. 309) suggestion that reading error differences between round dial and linear scales are attributable to variations in their "effective" area. The larger the area to be scanned, the less accurate the reading under conditions in which reading time is limited. This explanation appears to adequately account for the pronounced similarity among scale shapes when only central portions of each scale are considered. It does not, however, account for Graham's findings that vertical scales are significantly poorer than correspondingly designed horizontal scales. To account for this finding, Graham points out that objects subtending a visual angle of one-half degree at the eye can be detected if they lie within a field whose boundaries are approximately 100° to the right or left of the point of fixation, 70° above the point, or 80° below it. Thus, the width of the visual field is considerably greater than its height, and this is one factor which might favor the reading of round or horizontal scales, but would not work in favor of reading vertical scales. It might also be argued, however, that people are simply more highly trained in reading horizontally arranged materials (e.g., printed text), and that this highly trained skill interferes with a reading task incorporating vertically arranged materials. No test of the latter hypothesis was found in the literature reviewed.

Considering a control task rather than simply a display reading task, Mengelkoch and Houston (Refs. 233, 234 and 235) used a flight simulator to compare altitude tracking performance with a conventional three-pointer (MA-1) altimeter versus moving vertically-scaled altimeters. They found that altitude tracking performance was superior with the three-pointer altimeter only in comparison with a vertical tape altimeter which incorporated 1.5 inches of scale for each thousand feet of altitude. When the vertical tape scale factor was expanded to 2.375 inches for each thousand feet of altitude, performance using the vertical tape altimeter was essentially equivalent with performance obtained with the three-pointer altimeter. This is a very interesting finding when one considers that the MA-1 altimeter employs approximately 8 inches of scale for the maximum resolution scale of 1,000 feet of altitude.

Additional studies addressing the scale shape consideration were identified and reviewed, but were rejected because of methodological considerations of the types which have been

discussed previously, or because of a failure on the parts of the authors to clearly specify their performance measures or experimental tasks.

Of the studies which have been reviewed above, it can only be concluded that 20 years of research have produced no definitive answer to the question of whether circular scales are any different from linear scales in terms of the amount of time required to read them or the frequency of errors which result from such readings. Indeed, as it has been pointed out previously (Ref. 308) the manner in which scales are integrated into a total display context can have significantly greater impact than the independent design feature of scale shape. Nonetheless, there are sufficient data to indicate that scale shape is a potentially significant design consideration. Therefore, scale factor and graduation mark design considerations are discussed separately below for circular versus linear scales.

NONLINEAR SCALES

The majority of instrument scales are linear. As such, for all portions of the scale, the separation between graduation marks indicates the same numerical increment. Nonlinear scales are those which present a large range of displayed values into a relatively small space by compressing those portions of the scale for which highly accurate readings are not required. Typical examples include logarithmic scales in which scale factor on only one end of the scale is compressed while the other end is expanded. A variation on the logarithmic scale is the skewed scale. An additional class of nonlinear scale is one based upon a normal curve distribution, which could be used to expand either the center of the scale or the extremes of the scale.

Although nonlinear scales are most common to round or semicircular electromechanical displays, the moving pointer, vertically scaled vertical velocity indicator in the Air Force Integrated Instrument Panel is, in part, read against a nonlinear scale.

Several studies (Refs. 79, 82, 177 and 297) have investigated nonlinear scales, some in the context of altimeter design and others in more generalized display contexts including quantitative and checkreading tasks. It can be generally concluded from these studies that nonlinear scales produce little, if any, benefit in terms of scale reading accuracy. To be sure, the expanded portions of the scale can be read with a greater degree of precision, but if any readings must be made in the compressed portions of the scale, the related high precision associated with the expanded scale areas is proportionately

offset by imprecision in the compressed areas. Furthermore, Cohen and Dinnerstein (Ref. 79) report longer reading times for highly asymetrical logarithmic scales. They attribute their findings to the progressive changes in the meaning of graduation marks and scale intervals. In their study, the log $\sqrt{10}$ scale was effectively equal to the linear scale, and both of these scales were read significantly more accurately than either the log 10 or log 10^2 scale. The mean reading time was approximately 20% greater for the latter two scale configurations.

In the context of altimeter design, Innes (Ref. 177) compared linear and logarithmic altimeter scales. Display reading time varied between 1.5 to 3.0 seconds and subjects were required to perform the following tasks: read barometric altitude, read command altitude, determine the altitude difference and determine the direction of the difference. Criterion of correct response was established as being not more than one half a scale graduation (50 to 5,000 feet, depending upon position of pointer) from the exact positions of the barometric or command indices. Results of the study showed almost no differences between the two displays. Although relatively fewer reading errors occurred with the nonlinear scale, differences in terms of magnitude or direction of differences between actual and command altitude were comparable.

Considering the looseness of performance criteria used in some studies and the lack of performance advantage found in other studies, it would appear that there is little to recommend the use of nonlinear scales. On the other hand, studies reviewed have shown that reading errors or reading times only suffer for exaggerated nonlinearities. In this light, the following recommendations by Senders et al. (Ref. 297) appear justified. They indicate that logarithmic scales may be used with either normal or skewed distributions of pointer settings (those which emphasize the expanded portions of the scale) under the following conditions: (a) when allowable reading error tolerance is a constant proportion of the indication, so that larger errors can be tolerated on compressed portion of the scale, and (b) when there is a large preponderance of scale readings of the expanded end of the scale, and it is desirable to minimize reading errors in this portion.

NUMBERING SCALE INTERVAL VALUES

Scale intervals which are numbered are typically the major divisions of the scale. Typically, intermediate scale divisions are not numbered because of the display clutter which frequently results. Nonetheless, the pilot frequently must read displays at intermediate, un-numbered scale values; thus he is required to determine the numerical value associated with intermediate,

un-numbered scale graduations.

As one might expect, display reading times and reading accuracies are influenced by the scheme used to number major scale graduation intervals. The effect is most pronounced when scales must be read at un-numbered intervals or when scale interpolation is required. Scale interval numbering recommendations (Ref. 247) have been developed based upon studies such as those reported in Refs. 61, 115, 191, 192, 193, and 336. The recommendations may be summarized as follows:

(a) It is preferable for numbered graduation intervals to be in increments of one or decimal multiples of one (i.e., 1, 10, 100, 1,000, etc.).

(b) Numbered graduation intervals of two or five, or decimal increments thereof also may be judged as at least fairly acceptable. Examples are: 2, 4, 6 or 20, 40, 60, etc., .5, 1.0, 1.5, 2.0 or 5, 10, 15, 20, etc.

It has been consistently found, however, that scales numbered by 1, 10, 100, etc. are superior to other acceptable scales.

(c) Numbering scheme increments of .25 or .4 (or decimal multiples of these) or other even less common interval increments are not recommended since they produce both longer display reading time and greater reading errors.

In studies which are reviewed and interpreted in subsequent pages, emphasis was placed upon those which incorporated acceptable scale numbering schemes.

There also is some evidence indicating that the number of digits used to identify the numerical value of major scale graduations may influence display reading time and errors. Vernon (Ref. 336), for example, suggests that the maximum digit span for quick and accurate reading of numbers is three, unless the digits in excess of three are zeros. He further suggests that two-digit numbers are better than three-digit numbers. By inference it may be implied that single digits may be better than two. Some support for Vernon's position also appears to be provided by Grether (Ref. 149).

SCALE-TO-READLINE DISTANCE

The accuracy with which a scale can be quantitatively read is markedly influenced by the distance between scale marks and

the pointer or reference (fiducial) line against which the scale values are read. Indeed, minimizing the distance between scale marks and the index against which the scale is read is a necessary condition for accurate scale reading, and failure to satisfy this necessary requirement can invalidate the utility of best applications of other scale design considerations. This generally well-recognized relationship, however, appears to have been overlooked or ignored in the interest of aesthetics, at least in some electronic flight display designs (Ref. 206). The effects of violating this requirement are pronounced.

In an early study, Vernon (Ref. 336) used a tachistoscope to present simulated round dial and horizontal scales for viewing times of two seconds. All pointer settings corresponded directly with a scale marking; no interpolation was required. Scale markings were spaced approximately 0.5 inches apart. Vernon reports that reading errors were extremely small (1.5 to 4.4%) as long as the distance between the pointer and the scale markings did not exceed 0.5 inches. Scale reading errors increased markedly, however, for distances greater than this. It is easy to envision greater errors in situations where viewing times would be reduced or where interpolation would be required.

Churchill and Allan (Ref. 70) report a study in which subjects were required to read a variety of round dial displays, some of which incorporated a "staircase" arrangement for scale graduation marks. With this arrangement, the minor graduation marks used to divide intervals between major graduation marks became progressively shorter in length as the pointer approached succeeding major graduation marks. Two variations of the "staircase" scale were investigated. In one, the progressive shortening of minor graduation marks occurred on the outside circumference of the scale, allowing the pointer-to-scale distance to be held constant. In a second variation, the progressive shortening of minor graduation marks occurred on the inside circumference of the scale, producing a situation in which the pointer-to-scale distance progressively increased. The scales were read under two viewing time conditions: 1.5 seconds and subject-paced. A tachistoscope was used to present the simulated dials, and both interpolation and non-interpolation readings were required. Results of the study indicated that reading errors increased by 50% to 150% (depending upon other scale design features) for "staircase" scales which were designed such that the pointer-to-scale distance was not always minimal. The increases in error were statistically significant ($P<.05$). Churchill and Allen also reported that the "properly designed" staircase scale technique was no better than standard scaling in which minor graduation marks are equal in length.

In directly addressing the consideration of pointer-to-scale distance, Churchill (Ref. 68) used a tachistoscope to present simulated dial faces for either 0.3 seconds or subject-paced viewing times. The dial reading task required

interpolation of values between graduation marks. The pointer-to-scale distances investigated were zero, 0.125, 0.25, 0.50, 1.0 and 2.0 inches. Selected reading time and reading error data from the study are presented in Table 53, where it can be seen that reading errors increased markedly for pointer-to-scale distances of greater than 0.125 inches, and reading times were comparable for zero, 0.125 and 0.25 inch conditions. The zero and 0.125 inch conditions produced statistically comparable results. Viewing distance for the study was 28 inches.

Although the studies cited above all involved reading pointer positions against round dial scales, the principle of maintaining a minimal (no greater than 0.125 inch) distance between scale graduations and the reference or readline applies equally to linear scale reading tasks. This design consideration has been generally well taken into account in electromechanical moving tape displays by painting a readline directly on the glass which covers the display face. Hence, scale graduation marks pass behind the readline, and the only major problem is one of paralax resulting from the combined effects of display viewing angle and the amount of physical separation between the moving tape and the glass instrument face. A similar design solution appears reasonable for electronic displays, at least for those display modes in which scales are positioned on the display in a fashion which provides for a non-changing reference or readline. For any modes which may involve repositioning of scales, or the changing of scales in a manner which may also require a change in the physical position on the display face at which display readings are to be made, caution must be exercised to ensure that the interval between the shortest graduation mark and the readline does not exceed 0.125 inch in a direction perpendicular to the scale.

STROKE WIDTH OF SCALE MARKINGS

Three studies have dealt with accuracy of scale reading and scale interpolation as a function of the thickness of graduation marks. None of the studies involved an electronic display medium. Results of the various studies are not in total agreement, nor do the results of the studies consistently agree with typical human factors recommendations for graduation mark stroke widths.

In a series of comparisons, Loucks (Ref. 219) required subjects to make readings from alternative vertical velocity indicator designs in which the stroke width of both numerals and scale graduation marks was varied. Instrument reading times varied from 0.75 to 1.50 seconds. Loucks concluded that reading errors were lower and pilot preference higher for the 0.032 inch stroke width than for either the 0.016 or 0.048 inch stroke

Table 53. Effects of Scale Interval Length and Pointer-to-Scale Clearance on the Probability of Interpolation Errors and Reading Time for Subject-Paced Viewing. (Adapted from Churchill, Ref. 68)

		Scale Interval Length (Inches)						
		.25	.50	.75	1.0	1.5	2.0	*Total
Pointer Clearance (Inches)	Zero	.42	.22	.24	.14	.12	.11	.21 **(1.6)
	.125	.45	.16	.20	.13	.11	.12	.19 (1.5)
	.250	.53	.29	.23	.16	.08	.12	.23 (1.6)
	.500	.49	.36	.28	.15	.12	.13	.25 (1.7)
	1.000	.57	.41	.23	.14	.18	.13	.28 (1.8)
	2.000	.61	.44	.33	.27	.21	.17	.34 (1.9)

*Probability of error for all scale interval lengths.
**Mean reading time in seconds.

widths. This conclusion is in general agreement with typical human factors recommendations for stroke widths of scale graduation markings (Refs. 247 and 360). Woodson and Conover (Ref. 360), for example, recommend that major scale graduations for aircraft instruments be 0.035 inches in thickness; intermediate graduation marks should be 0.030 inches; and minor graduation marks should be 0.025 inches in thickness.

Two additional studies have investigated scale interpolation error as a function of graduation mark stroke width. Carr and Garner (Ref. 59) investigated stroke widths of 0.004, 0.008 and 0.016 inches, and found that magnitude of scale reading error was not affected by graduation mark stroke width for scale intervals ranging from 0.02 inches to 10.0 inches. This finding appears to have little direct application, however, in light of Louck's findings that stroke widths smaller than 0.032 inches have a negative impact upon scale reading.

Topmiller (Ref. 330) investigated precision of interpolating pointer settings to tenths of a scaled interval accuracy using a scaled interval of 0.40 inches. Graduation mark thicknesses of 0.04, 0.08, 0.12, 0.16 and 0.20 inches were compared. A hairline condition also was examined, apparently using an actual hair as the scale mark. Topmiller found that reading error was considerably smaller and highly comparable for the 0.12 and 0.16 inch stroke widths. Either thinner or thicker stroke widths produced from 50% to 75% greater reading error. It can be noted that Topmiller's findings do not closely agree with other findings discussed above. One reason may lie in the fact that large stroke width differences between graduation marks and the pointer allowed Topmiller's subjects to rely upon vernier acuity factors in reading pointer settings. This would be of probable advantage if the subjects were aware of the ratio of stroke widths of the pointer and the graduation marks, allowing them to estimate displayed values by assessing the degree to which the pointer overlapped the various graduation marks.

Although Topmiller's data do not agree closely with other stroke width data or human factors recommendations, one trend which is apparent from the available human factors data is that graduation mark stroke width definitely may have an impact upon scale reading and interpolation error. Because of the lack of consistency in the data, and because none of the available data have been generated in an electronic display context, it would appear necessary to apply existing human factors guidelines, such as those contained in References 247 and 360, with caution and only after verification studies have been performed.

All other research reports which were reviewed examined stroke width in the context of alphanumeric or geometric symbols. In these contexts, stroke width typically is expressed as a percent of symbol height. No study was found in which the effects of stroke width (scale graduation mark thickness) was examined in an electronic display context and in relation to a scale reading task. There is evidence (e.g., Refs. 36 and 303) to indicate, however, that an optimum stroke width for scale markings and other line-constructed symbology such as horizon lines, vector lines or course indications, may be influenced by the following variables: number of raster lines, ratio of widths of active to inactive raster lines, bandwidth, contrast ratio, and length of the scale graduation marks. No data exist which clearly apply to these considerations.

SUBDIVIDING MAJOR SCALE INTERVALS: READING TO NEAREST SCALE MARK

Number of Scale Division

The manner in which numbered intervals are subdivided by minor graduation marks also can have a marked impact upon scale reading errors. Vernon (Ref. 336), in fact, reports that the most frequent cause of scale reading errors was the manner in which numbered scale intervals were subdivided by minor graduation marks. He compared displays in which major scale intervals varied in the manner in which they were subdivided. He concluded the following: scale intervals divided into tenths were read more accurately than those divided into quarters, obviously because of the requirement for interpolation with the latter scale division scheme. But more important, even for major scale increments in multiples of 10 (a highly recommended scale numbering sequence), serious scale reading errors occurred when the scale was divided into eighths or sixteenths. When minor graduation marks were at eighths of the major scale interval, 69% of the scale settings were misread; when sixteenths were used, 96% of the readings were in error. On the other hand, almost all scales numbered in tens and subdivided into fifths, tenths, halves or quarters were read correctly.

Spacing of Minor Graduation Marks

A second consideration in selecting the number of scale subdivision (minor graduation marks) involves a speed versus accuracy tradeoff, and is based upon the degree of accuracy to which a scale must be read in terms of operational requirements. It is known, for example, that scales can generally be read with greater accuracy if minor graduation marks are provided for each scale value which the operator must read (e.g., Refs. 115 and 190). This rule applies only up to the point at which the scale becomes "cluttered" by a profusion of scale division marks. Unfortunately, there are no quantitative guidelines for defining the point at which scales generated on electronic displays may become "cluttered". Kappauf and Smith (Ref. 193), however, have shown that the probability of misreading single unit scale marks is practically zero as long as the scale marks are at least 0.09 inches apart. Error increases slightly (approximately 2%) for scale spacing of 0.04 inches. With scale spacing of 0.02 inches, errors increased to approximately 13%. Evidence substantiating the Kappauf and Smith data are reported in Reference 109. It would appear, therefore, that scale clutter may occur when minor scale graduation marks are separated by less than 0.05 inches, at least in the context of printed display scales.

The addition of scale marks at scale positions where readings must be made minimizes the necessity for the operator to interpolate between scale marks. If, however, his task is to "read to the nearest scale mark", the addition of more scale marks results in a penalty in terms of the amount of time which must be spent reading the scale (e.g., Refs. 115, 190 and 336). Data from Elkin's study (Ref. 115) are exemplary and are shown in Table 54. The table also shows the effects of number of graduation marks and corresponding requirements for interpolation upon quantitative scale reading accuracy. It is apparent from the table that one scale design cannot maximize reading accuracy while minimizing reading time. To the extent that either time or accuracy is more important from an operational standpoint, scale design must vary accordingly.

Also, apparent in Table 54 is an answer to the question: "What happens to reading accuracy if I have more scale marks than my accuracy requirement necessitates?" Assuming that the "extra" marks do not produce "clutter", it would appear that "extra" scale marks have an almost negligible influence upon scale reading accuracy.

In instances where reading accuracy is important and multiple minor graduation marks are used, the interval separating the minor graduation marks can influence reading accuracy, even when scale readings are made only to the nearest scaled interval. Data generated by Kappauf (Ref. 189) are exemplary of this and are shown in Table 55. It can be seen from Table 55 that probability of misreading scaled value decreases as the interval between minor graduation marks which indicate the scaled value increase up to 0.09 inches. Furthermore, display reading time decreases as the amount of space dedicated to each scale increment increases. Unfortunately, few data exist which corroborate these findings or allow for meaningful projections of the effects of probability of scale reading error for even greater distances between minor graduation marks. For example, under comparable conditions, scale reading error data reported by Christensen (Ref. 67) and Elkin (Ref. 115) do not agree in magnitude with the data in Table 55. Furthermore, Elkin (Ref. 115) reports that substantially similar reading errors occur whether the distance between minor graduation marks was 0.06 inches or 0.30 inches.

Once again, it is apparent that differences in research methodology can have most pronounced effects upon design recommendations. In light of these differences, however, it would be most desirable to assume a "worst-case posture", and go along with the findings of Kappauf (Ref. 189) on the assumption that even one demonstration of an effect is worth the display designer's attention. On this basis, it is most reasonable to assume that approximately 0.1 inches per minor scale graduation is to be preferred, at least based upon data derived from studies dealing with electromechanical display design. This recommendation, however, is totally untried for electronic display design, and extreme caution must be exercised in applying it.

Table 54. Time and Error Scores for Four Conditions of Quantitative Scale Reading*. (Adapted from Elkin, Ref. 115)

	Scale Graduation and Reading Conditions							
	5/5		1/5		1/1		5/1	
	Rt.**	%E***	Rt.	%E	Rt.	%E	Rt.	%E
Open-Window Display	1.02	.85	1.03	0.85	1.21	0.00	1.22	12.10
Round Dial Display	1.13	2.50	1.16	2.90	1.47	2.50	1.39	9.15
Vertical Linear Scale Display	1.18	3.35	1.18	0.40	1.49	3.35	1.43	13.75

*Based upon subject-terminated conditions.
**Display reading time.
***Percent of display readings in error.

5/ scale graduated by fives
1/ scale graduated by ones
/5 scale read to nearest five
/1 scale read to nearest one

Table 55. Probability of Scale Reading Error as a Function of the Interval Between Minor Graduation Marks. (Adapted from Kappauf, Ref. 189)

Distance in Inches Between Minor Graduation Marks	Probability of Misreading Minor Scale Graduation Marks
.02	9.6%
.04	3.8%
.09	1.5%

CIRCULAR SCALES: INTERPOLATION

When scales must be read to accuracies greater than those associated with individual graduation marks, the observer is required to interpolate distances between graduation marks. When interpolation is required, scale intervals must be expanded beyond those found adequate simply for reading "to the nearest scale mark".

A review of the literature applicable to circular scale indicates that the degree of accuracy associated with scale interpolations is a function of two primary variables: arc length of the interval separating graduation marks; and the degree of interpolation accuracy which is required.

Considering just studies in which scales were divided into tens and subjects were required to read the scales to units, a remarkable degree of consistency is found in the experimental literature. The experimental data indicate that accuracy of interpolation increases as the distance between graduation marks increases up to approximately 0.75 inches. This finding applies whether reading error is measured in terms of the probability of occurrence of specified magnitudes of reading inaccuracy (Refs. 192 and 193) or whether magnitude of reading error is expressed as a percent of the scale interval (Ref. 150). For scales divided into fives and read to units, accuracy of interpolation increases as distance between graduation marks increases up to approximately 0.30 inches (Refs. 192 and 193).

Kappauf and Smith (Refs. 192 and 193) investigated scale interpolation accuracy for scales divided into either fives or tens. Considering first the scales divided into tens, they required subjects to read each scale to one unit of accuracy. Consequently, subjects had to estimate pointer positions to tenths of the distance between scale marks. Distances between scale marks was varied from 0.11 inches to 1.76 inches. Reading time was subject paced; on the average, 1.6 seconds was spent reading each display. Data from the study indicated that approximately 99% of the readings which were in error were in error by only one or two scale units. These were termed "local errors" by Kappauf and Smith. Only about one percent of the errors were as great as five scale units. Figure 82 shows the average probability of occurrence of "local errors" for each graduation interval studied as well as for interval numbering of fives and tens. The data in Figure 82, therefore, show the probability of reading errors of approximately 20% of the scaled interval for the tens scales (i.e., reading errors of up to two units for a ten-unit scale interval) and approximately 40% of the scaled interval for the five scales (i.e., reading errors up to two units for a five-unit scale interval).

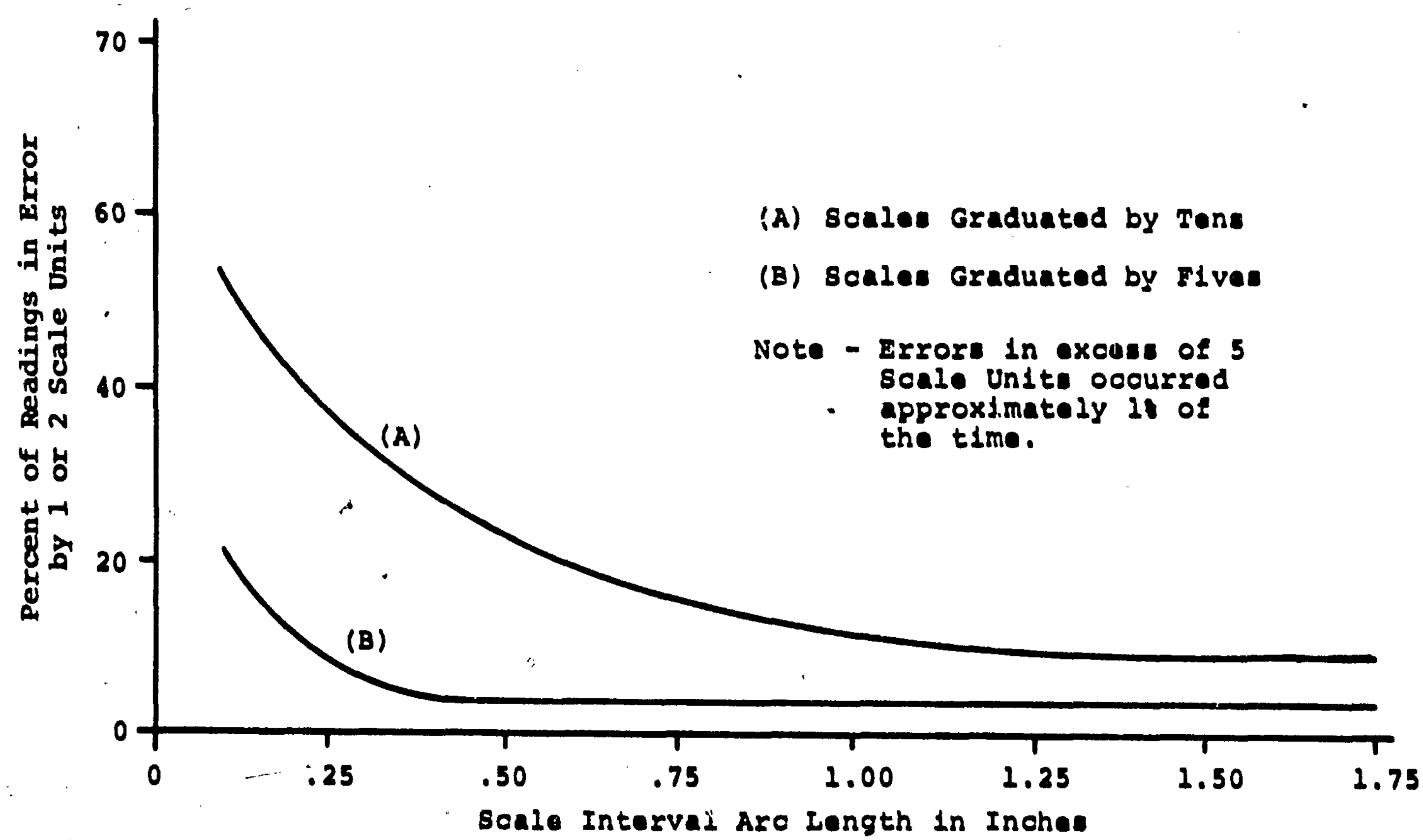


Figure 82. Probability of Minor Scale Reading Errors (1 or 2 Units) as a Function of Scale Interval Length. (Adapted from Ref. 192)

The trends in Figure 82 are quite different for the fives scales and the tens scales. As might be expected, reading error minimized at shorter scale intervals for scales marked in fives due to the less stringent interpolation requirement. Also of interest is the observation that error rates reached much lower levels for the fives scales than for the tens scales, even under conditions wherein the same arc length of scale was used for each unit on the two scales. Apparently this difference is due to the fact that in situations where equal arc lengths are devoted to each scale unit, the arc distance between graduation marks for scales marked at each fives units is one-half the distance which occurs between graduation marks of scales marked at tens. Accordingly, the distance which must be visually fractionated by the observer is less for scales marked at fives, and the task of visually dividing the smaller distance into fifths is easier than dividing twice the distance into tenths. Furthermore, interpolation task difficulty appears to be an increasing power function of scale interval. As such, doubling the physical distance within which this interpolation must be made more than doubles the difficulty of the interpolation task, at least in terms of probability of reading error on the order of one or two scale units. This relationship, however, does not appear to manifest itself in terms of larger reading errors or time required to make the interpolation.

Taking a somewhat different approach in terms of measuring error of interpolation, Grether (Ref. 150) expressed imprecision in scale reading in terms of percent of the scaled interval. Data from Grether are shown in Figure 83. Grether's data are comparable with those of Kappauf and Smith for intervals graduated by tens.

Using Grether's metric, it would appear that reducing the graduation interval below 0.60 inches will have a negative influence upon interpolation accuracy. This agrees closely with Kappauf and Smith's finding of 0.75 inches. Correspondingly, both the Grether studies and the Kappauf and Smith studies show that expanding the graduation interval beyond these points does little if anything to enhance scale interpolation accuracy. The reader is reminded again, however, that interpolation accuracy also is a function of the numerical value assigned to each scale interval (e.g., 5's vs 10's), and a choice exists for the designer as to whether he should subdivide scale intervals and provide uncluttered graduation marks at each reasonable value to which a scale should be read, or whether he should design with optimum interpolation in mind. The answer to these questions lies with the designer.

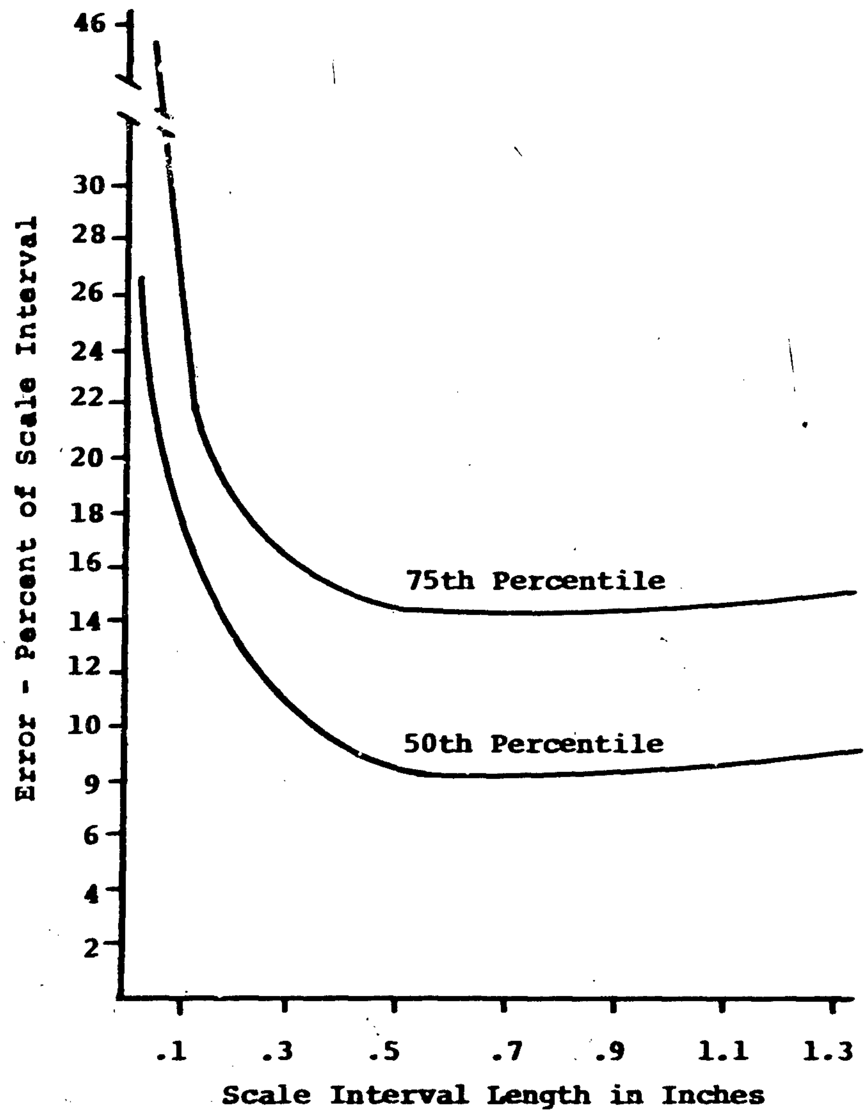


Figure 83. Scale Reading Error as a Function of Scale Interval Length. (Adapted from Ref. 150)

LINEAR SCALES: INTERPOLATION

Introduction

Applicable research dealing directly with the legibility of either vertical or horizontal linear scales is considerably less conclusive than comparable circular scale research. Indeed, only three different experimental studies are reviewed below in relation to linear scale legibility, and the reader is advised that the amount of agreement among the findings of these studies is not high. None appear to provide conclusive design guidelines, at least in comparison with the data available for circularly scaled displays.

Interpolation Accuracy

In two early studies, Churchill (Refs. 68 and 69) investigated interpolation accuracy for vertical scales in which graduation marks were spaced from 0.25 to 3.00 inches apart. Viewing distance was 28 inches. Subjects read the position of a pointer to an accuracy of one-tenth of each scaled interval. Consequently, the criterion of reading accuracy varied with scale factor, and Churchill's data do not present the probability of making constant accuracy interpolations a function of the distance separating graduation marks. His data do show, however, the probability of correctly interpolating vertical scales to within 10% of intervals.

In his first study, Churchill (Ref. 68) did not systematically vary display reading time. Each subject was instructed to read the simulated displays as quickly and accurately as possible. Reading error and reading time data from the study are shown in Figure 84 where it can be seen that percent of readings in error tended to decline with increasing graduation mark separation up to about 1.00 inches, whereafter increasing the separation produced only very slight further decreases in interpolation error. Mean time to make a display reading, on the other hand, failed to show any sizeable decreases for separations greater than 0.75 inches. Churchill did not publish detailed statistical analyses, and it is unknown at what graduation mark intervals performance failed to become significantly better in a statistical sense.

In a second study, Churchill (Ref. 69) essentially repeated his earlier experiment with one significant change. In the second study, display reading time was controlled and limited to 500 milliseconds. Data from the second study also are shown in Figure 84 where it is apparent that reducing the display viewing time produced considerably more interpolation errors. Again, however, Churchill demonstrated that reading accuracy improved with increased scale separation up to 1.00 inches, thus confirming the trend shown in his earlier data. Unlike his

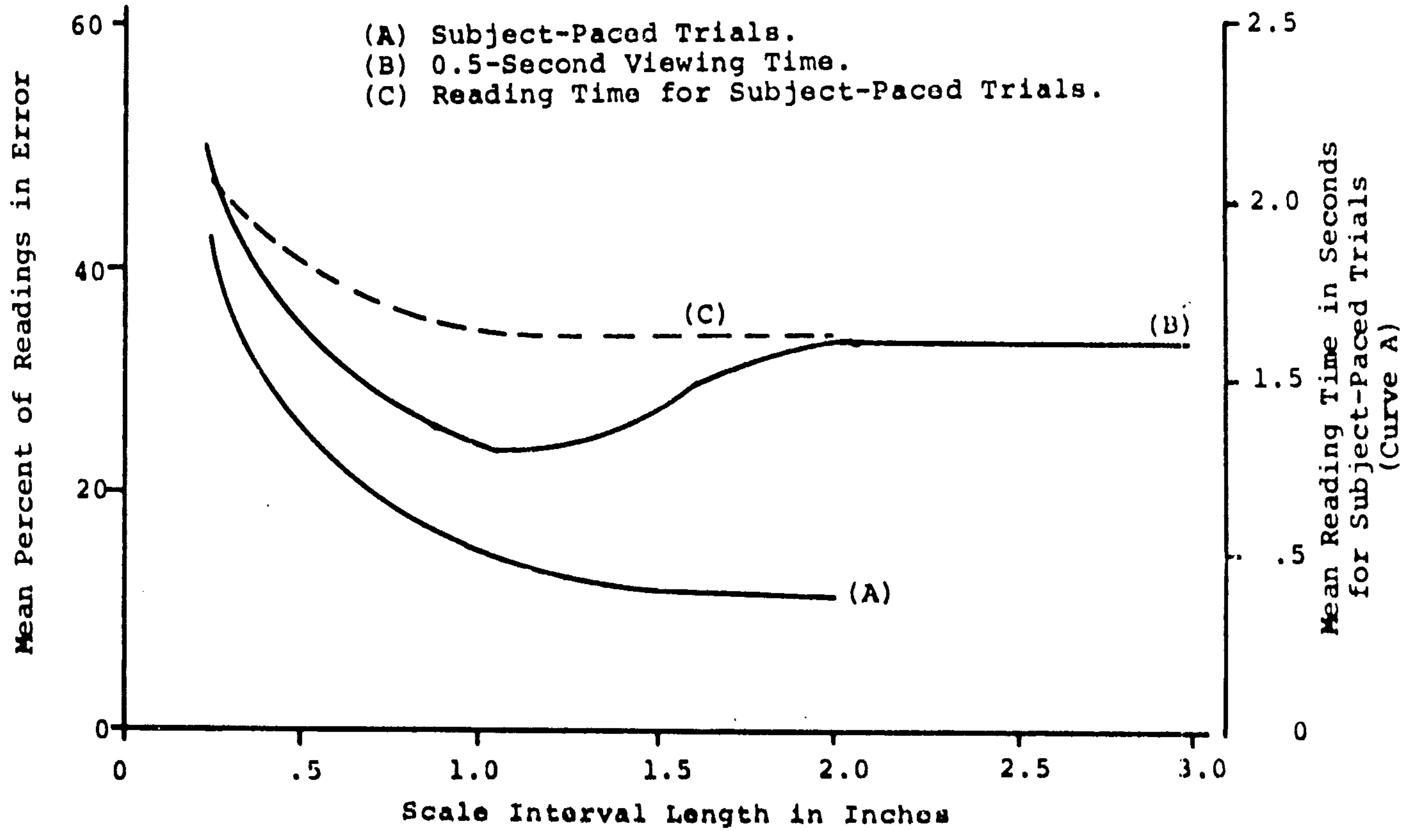


Figure 84. Reading Errors and Times for Vertical Scales as a Function of Scale Interval Length. (Adapted from Refs. 68 and 69)

earlier data, however, reading errors from the second study showed a trend to increase for scale separations greater than 1.00 inches. A similar trend also is reported by Kelso (Refs. 201 and 202) in that she also found improved reading accuracy with increased scale factor only up to a point, beyond which increased scale factor resulted in a performance decrement.

Carr and Garner (Ref. 59) reported an experiment in which subjects were requested to estimate the position of a pointer to the nearest 100th of an interval using a horizontal scale. The scales were viewed at a distance of 20 inches, and display reading time was not reported. All experimental trials, however, were subject-paced. Reading error was defined as the difference between actual and estimated pointer position measured in millimeters. No statistical analyses were reported.

Data from Carr and Garner's study are shown in Figures 85 and 86. It is apparent from Figure 85 that reading errors, expressed as a percent of the scale interval, were never in excess of 10%, even for relatively small intervals. It is further apparent that error showed a continuous decreasing trend for graduation intervals up to 20 millimeters (0.8 inches), but that decreases in error were quite small for scale intervals greater than 15 millimeters 0.6 inches). Assuming a constant visual angle, scale intervals at a 28-inch viewing distance corresponding with the 15 millimeter scale interval would be approximately 0.85 inches.

By far the most comprehensive linear scale legibility study is reported by Kelso (Refs. 201 and 202). She investigated the combined effects of the following variables upon reading time and the absolute error of interpolation: scale orientation, vertical and horizontal; scale factor (i.e., the distance in inches between major numbered graduation marks), 1.38, 1.88 and 2.38 inches; and number of graduation marks used to subdivide each scale factor interval, zero, one, three, four and nine. She defined absolute error as the scale value difference between actual and reported scale values. One hundred and fifty Air Force officers participated in the study. The various combinations of simulated scales were rear-projected onto a viewing screen which was located 28 inches from the subject's eyes. The subject's task was to read each displayed value to the most accurate value which he felt he could. In this respect, Kelso's study differs from practically all other scale legibility studies in that subjects were not instructed to read each scale to a pre-determined level of accuracy, such as tenths or hundredths of a scale division.

Reading error data from the Kelso study are shown in Figures 87 and 88. Reading time data are shown in Table 56. The error data correspond to reading error magnitudes (in scale units) which would be expected if the scales were graduated in one-unit increments at each major scale graduation. The reader's attention is drawn to two general trends in these data. First,

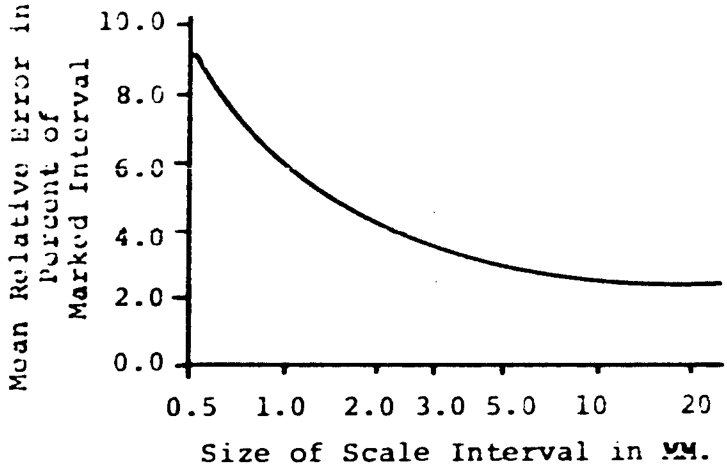


Figure 85. Relative Error of Visual Interpolations in Percent of the Scale Interval as a Function of the Size of the Scale Interval. (Adapted from Ref. 59)

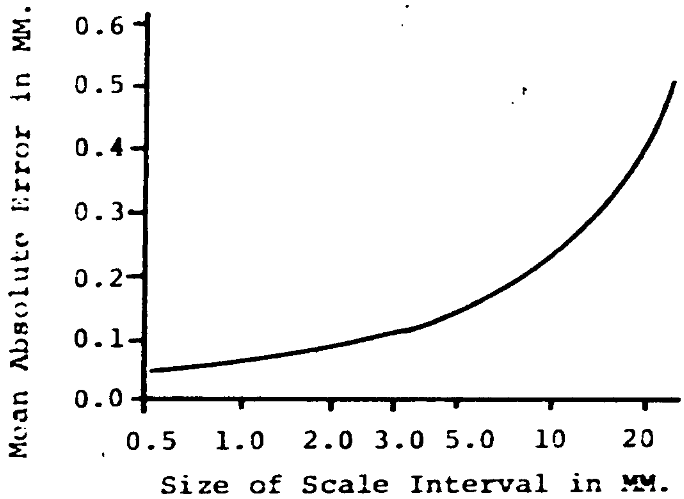


Figure 86. Absolute Error of Visual Interpolations in MM. as a Function of the Size of the Scale Marked Interval. (Adapted from Ref. 59)

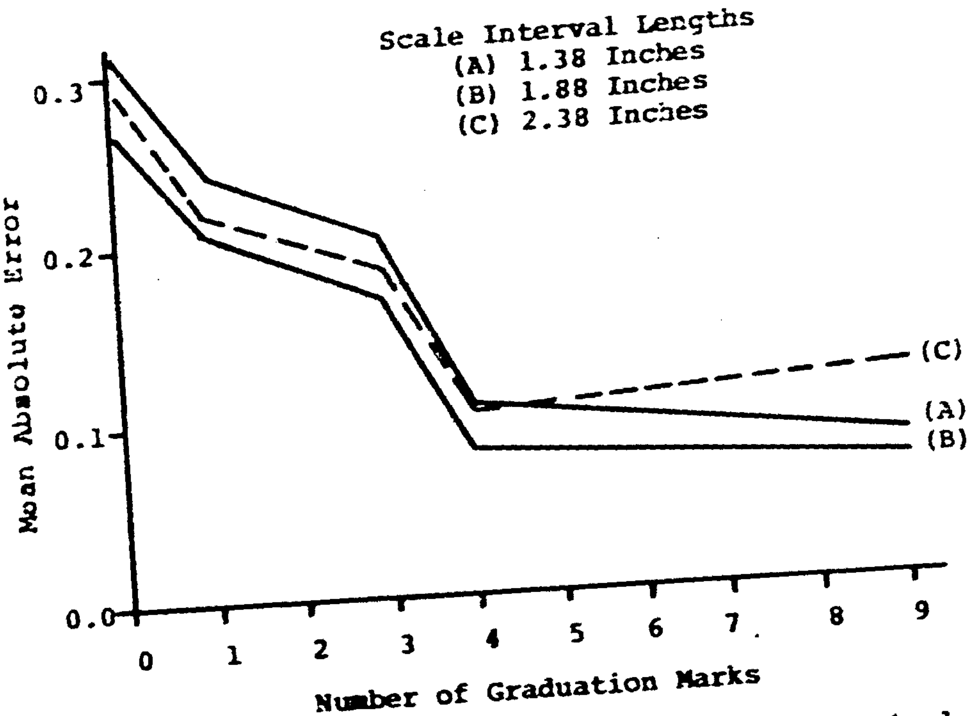


Figure 87. Mean Absolute Error as a Function of Vertical Scale Interval Length and Number of Graduation Marks Per Interval. (Adapted from Ref. 201)

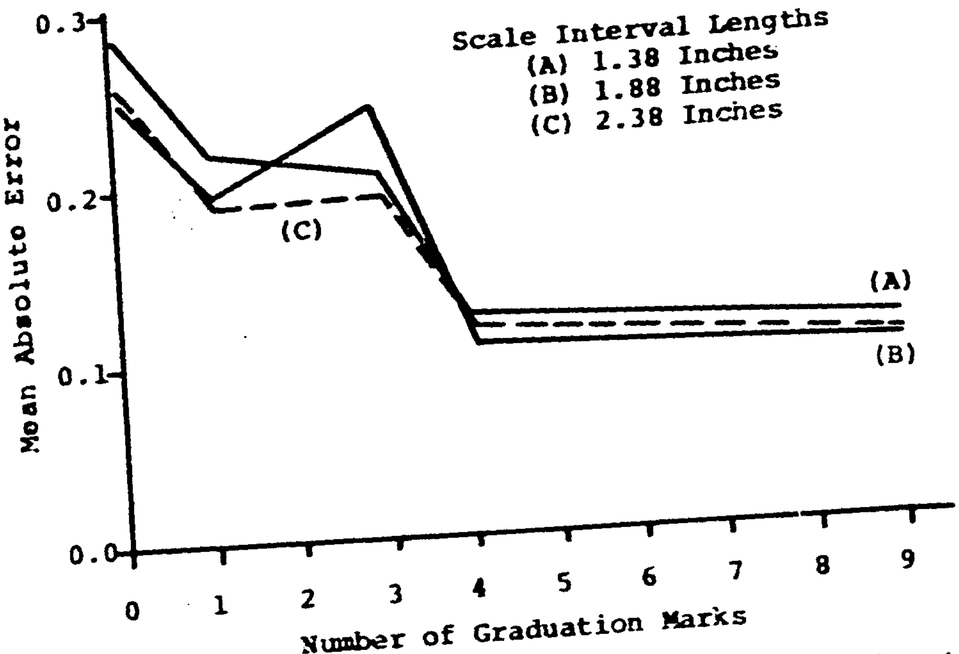


Figure 88. Mean Absolute Error as a Function of Horizontal Scale Interval Length and Number of Graduation Marks per Interval. (Adapted from Ref. 201)

Table 56. Mean Display Reading Times in Seconds as a Function of Scale Orientation, Interval Length and Number of Graduation Marks per Interval. (Adapted from Ref. 201)

	Scale Interval in Inches	Number of Graduation Marks 0	1	3	4	9
VERTICAL SCALES	1.38	5.5	3.8	4.1	4.5	3.7
	1.88	5.8	3.6	4.0	4.6	3.6
	2.38	6.1	3.8	4.3	4.8	3.6
HORIZONTAL SCALES	1.38	5.6	3.6	4.0	4.8	3.5
	1.88	5.4	3.7	4.0	4.6	3.4
	2.38	5.8	3.6	4.0	4.5	3.4

display conditions which produced shorter reading times did not produce higher reading accuracies. This is consistent with the findings of other display legibility research. Displays which may be read quickly may not necessarily be read accurately. The second trend involves reading time data only. Mean reading times ranged from 2.6 to 6.4 seconds. Practically all of the mean reading times reported by Kelso are considerably greater than reading times reported in any other study of display legibility research. Kelso also observed this situation and attributed her longer reading times to the demanding accuracy criterion which she instructed her subjects to use. Although this appears as a reasonable explanation, it is felt that the reading accuracy findings published by Kelso must be interpreted cautiously in light of the exceptionally long times which subjects required to make at least some display readings, and the corresponding large differences between such reading times and "typical" eye fixation times associated with reading cockpit displays.

Considering first the results as they apply to vertically scaled instruments, the following conclusions can be drawn:

- The 1.88 inch scale factor produced significantly (P=.05) smaller reading errors than did the 1.38 or 2.38 inch scale factor displays. Mean reading errors were statistically comparable for the 1.38 2.38 inch scale factor conditions.

- Conditions incorporating either 9 or 4 graduation marks resulted in smaller mean errors than the 3, 1 or zero graduation mark conditions. Performance was statistically comparable for the 9 and 4 graduation mark conditions. The use of 3, 1 or zero graduation marks not only produced greater mean reading error, but the magnitude of error became significantly greater for each reduction in the number of graduation marks.

- Similar trends were apparent from the analysis of standard deviations of the reading error data.

- Reading times were affected primarily by the number of graduation marks, and were relatively unaffected by scale factor.

Considering the results as they apply to horizontally scaled instruments, it is apparent that trends in the data are somewhat different from those associated with vertical scale instruments. The following conclusions can be drawn:

- Scale factor had no statistically significant impact upon reading error for the horizontal scales.

- The effect produced by graduation marks is similar for horizontal and vertical scales. Either 9 or 4 graduation marks resulted in statistically similar reading error. Either 9 or 4 graduation marks was superior to 3, 1 or zero graduations.

Either 3 or 1 graduation mark resulted in statistically comparable reading errors. Performance was poorest with zero graduation marks.

- Similar trends were apparent from the analysis of standard deviations of the reading error data.

- Reading times were affected primarily by the number of graduation marks, and were unaffected by scale factor.

Comparison Among Studies

Data generated by Churchill or Kelso can only be directly compared for the vertical scales. Any comparison of the data produced by the two researchers, however, indicates a lack of consistency, even considering that the two employed somewhat different reading accuracy criteria. In two studies, Churchill found that interpolation error was minimized when about one inch of scale distance separated adjacent graduation marks. This finding held for display reading times of approximately 0.5 or 1.7 seconds. Kelso, on the other hand, has shown that interpolation error is minimized when about 0.19 inches of scale distance separated adjacent graduation marks. This rather marked, apparent reduction in graduation mark separation, however, appears to have been achieved at the expense of display reading time since Kelso reports that associated mean reading times varied between 3.6 and 4.6 seconds. Additionally, Kelso's data are not in close agreement with prior research (e.g., Refs. 115 and 190) which has shown that reading accuracy improved with the addition of graduation marks, provided that the numbers of marks produce neither clutter nor confusing scale subdivision units. Once again it may be suspected that the exceptionally long display reading times reported by Kelso may have been a direct contributor in this respect. Finally, data reported by either Churchill or Kelso are in total disagreement with similar data generated within the context of circular scale displays. As noted previously, interpolation accuracy for circular scale displays ceases to show any meaningful improvement for distances between minor graduation marks much in excess of 0.50 to 0.75 inches. Findings published by Carr and Garner, however, are in close agreement with circular scale data.

In light of the degree of inconsistency found among the data dealing with the design of either vertical or horizontal scales for maximum readability, it would appear that it is still necessary to experimentally verify that new vertical or horizontal scales are designed to meet specified readability requirements, at least when scale interpolation is anticipated.

CHECKREADING CUES

It has long been recognized that certain additions to basic scales assist the operator in identifying out of tolerance or undesirable values of a parameter. Perhaps one of the most well-known such checkreading cue is the command index of the type frequently used on vertical tape flight data displays. It has also been pointed out (Ref. 230) that the use of the color can facilitate a qualitative checkreading task. Typically, red is used to indicate a danger condition, yellow indicates caution, and green is used to indicate normal or acceptable performance. As noted in the report section titled INFORMATION CODING, however, the use of color may not be necessary in electronic flight data displays. Consequently, the use of color for checkreading cues should be approached with caution, and then only after other coding techniques have been exhausted.

The remaining coding technique which has application in providing checkreading cues is shape coding. Typical (Refs. 230, 247 and 360) shape coding recommendations which have potential application to electronic flight data display scales include the following: a cross-hatched or angularly striped area to denote an undesirable condition; a sawtoothed-edged area to denote a dangerous vibration condition; a thick line running perpendicular to graduation marks to indicate normal operating range; an uncoded interval between a normal operating range code and danger condition code to indicate an inefficient operating condition.

No hard and fast, quantitative rule exist for assisting the display designer in determining when to use shape coding on scales. Similarly, no studies were identified which explored design factors for shape codes in the context of electronically generated displays.

RESEARCH RECOMMENDATIONS

Although numerous experimental investigations have addressed design considerations for scale readability, it is apparent that additional research is required. Research requirements stem from three primary considerations. First, prior applicable research conducted in electromechanical display contexts has frequently produced inconclusive and occasionally contradictory findings. Consequently, there is not a solid base from which to generalize to the electronic display medium. A second consideration is that scale legibility research has not always produced the type of data which is most useful in making design tradeoff decisions. Much of the research done to date has centered around identifying the combinations of scale design

factors which produce maximum precision of scale legibility. One must ask, however, maximum legibility for what? Many parameters of information displayed in the cockpit must be read only to pre-specified tolerance levels, and there are marked voids in knowledge regarding the effects of combinations of scale design factors relating to operationally-based legibility requirements, including both accuracy and time. Finally, no research studies were found, either past or on-going, which directly investigated scale legibility in an electronic display context. The closest studies involved transilluminated display techniques such as rear-projection of stimulus materials, but even these techniques have not addressed problems with resolution or contrast ratio.

All of the research recommendations identified below assume straight scales, both vertical and horizontal. Furthermore, linear scales are assumed, as are proper numbering schemes for scale intervals and the use of a suitable numeric font and size. Finally, an electronically generated direct view display and a 28-inch viewing distance are assumed. Several categories of research follow.

Scale Shape

There is sufficient evidence in the literature to indicate that readability data generated using either a vertical or a horizontal scale may not be directly generalizable to the other scale orientation. Consequently, each research topic discussed below should be investigated for both display orientations.

Aperture Size

Aperture size refers to the total range of scale which is visible. There is evidence to indicate that aperture size may have an impact upon both the speed and accuracy with which straight scales can be read. However, there are no data which investigate the effects of a wide range of aperture sizes upon either speed or accuracy of scale readings. It is recommended, therefore, that aperture sizes ranging from two to eight inches be investigated for their influence upon scale reading times and reading errors.

Readline Configurations

The readline, or fixed reference against which a scale is read, merits at least some exploratory investigation, even if only in the context of verifying that assumed readline configurations will provide acceptable scale legibility. The problem appears less pronounced for readlines which are physically part of the display, such as those painted on the display face. When, however, readlines are electronically generated, it is mandatory that the readline be conspicuous and easily discriminable from other display symbology. In this regard, the

area, stroke width, or geometric form of the readline is particularly important. Indeed, a very meaningful comparison would involve painted versus electronically generated readlines configurations. Additionally, contrast ratio requirements must be established for readlines just as they must yet be established for other display symbology. Similarly, resolution variables including bandwidth, number of active raster lines, or spot (emitter) size for digitally addressed displays require examination. Because scales are used for making both quantitative readings and for checkreading, it would be highly desirable to investigate the effects of reading characteristics for both types of tasks. Reading error rate, error magnitude, and reading time are relevant indices of performance.

Stroke Width and Length of Scale Markings

Human factors recommendations and Military Standards exist for lengths and stroke widths of scale markings only for electromechanical displays. None exist, however, for electronically generated flight displays. It has been demonstrated that variations in stroke width can impact upon the precision with which scale values can be interpolated. Indeed, because many electronically generated display elements frequently are comprised of line segments, it would be appropriate to investigate scale markings within the more general context of line dimensions. Either way, the following display variables require exploration: Factors of resolution including as appropriate bandwidth, number and width of raster lines, or spot (emitter) size. Again, contrast ratio requirements remain to be established for the spectrum of cockpit ambient brightnesses, eye adaptation levels, and display background brightnesses which may be anticipated.

Line Dimension

Within this general context of variables, it appears reasonable to investigate line stroke widths ranging from 0.015 to 0.10 inches. For application to the construction of scales, line lengths ranging from 0.10 to 0.75 inches should be explored with the objective of identifying three readily discriminable line lengths for use as major, intermediate and minor graduation marks. Longer line lengths up to 10 inches also should be investigated with the objective of identifying not only stroke width requirements, but also display system requirements for ease of legibility and discriminability. Finally, it is recommended that the line dimension research described above include various orientations of the lines and scales on the display face up to 90 degrees from vertical in order to provide data on the combined influences of resolution, emitter shape, bandwidth, contrast ratio, etc., upon line dimension requirements throughout the total range of aircraft roll attitudes. Experimental tasks should include discrimination among lines of various length in a display scale context, scale reading to the nearest

graduation mark, scale interpolation, and vernier acuity as a function of line orientation. Appropriate performance indices are: probability of reading error, probability of reading error of pre-selected magnitudes based upon scale reading performance requirements, and display reading time.

Spacing of Graduation Marks

When graduation marks are not adequately separated, scale clutter occurs, and scale reading performance deteriorates. Experimental evidence generated using simulated electromechanical displays indicates that the effects of clutter may become apparent when graduation marks are separated by less than 0.04 inches. Electronically generated display images, however, may not be characterized by the high degree of resolution inherent in printed display scales. Accordingly, spacing between graduation marks requires at least limited investigation if only to identify the limits of display scale crowding or clutter beyond which operator performance can be expected to suffer. Graduation mark spacing from 0.04 to 0.25 inches should be explored in the context of a scale reading task which requires the operator only to read the scale to the nearest scale marking. Probability of error and reading time data are required. This research topic should assume that suitable basic line dimension criteria have been established, as well as legibility contrast ratio requirements, and should be based solely upon establishing criteria of scale clutter in relation to display system resolution.

Scale Factor

The area in which straight scale legibility research is most lacking and where the greatest conflicts among existing data occur is with regard to the required spacing between adjacent graduation marks necessary to produce pre-specified accuracies in scale interpolation tasks. Based upon research conducted with actual or simulated electromechanical displays, it would appear that quick and accurate reading of scales to the nearest graduation mark can be accomplished when graduation marks are spaced at least 0.10 inches apart. However, it is to be expected that accuracy of interpolation would not be precise with this scale factor.

The performance data which the designer needs relate to the probability of the pilot's consistently making scale readings to a specified degree of precision. For example, the designer who is charged with designing the heading scale for a flight director display may be concerned with identifying the scale factor which will ensure that the pilot will be able to read heading to + 0.5 degrees 90% of the time. In this example, it can be noted that the hypothetical designer is not, for example, asking: "What scale factor will provide absolutely the highest degree of precision in reading heading from a horizontal scale?" It is

recommended, therefore, that scale factor research be conducted, but with the objective of establishing probability of reading error for a family of pre-selected reading accuracy requirements. Additionally, it is recommended that controlled display reading times of 500 and 1,000 milliseconds be used in addition to subject-paced display readings. With these values in mind, it is recommended that research be accomplished in order to identify and quantify effects of the following scale design variables:

- Scale orientation, including both vertical and horizontal.

- Distance separating minor graduation marks, ranging from 0.10 to 1.50 inches.

- Contrast ratios required to maximize display reading performance for all combinations of the variables above.

SECTION VII

FACTORS AFFECTING VISUAL ACUITY

INTRODUCTION

Visual acuity is operationally defined as the reciprocal of the angle in minutes of arc subtended by the smallest detail which can be resolved by the human eye under a given set of viewing conditions. Values of visual acuity vary as a function of the type of visual target presented, the type of display system used to present it, the environmental conditions under which it is viewed, and the method of measurement employed. Five measures of acuity are commonly used (minimum visible, minimum perceptable, minimum separable, vernier and steroscopic). Minimum separable acuity is the measure most useful for display design purposes. Minimum separable acuity is defined as the minimum amount of separation necessary for two light sources (or two non-luminous images, i.e., parallel bars) to be perceived as distinct objects.

Poole (Ref. 268) states that if the average engineer is asked to specify the limits of visual acuity for the human eye, the figure one minute of arc will automatically be elicited, but without any qualifying circumstances. Technically, this value refers to the generally accepted resolving power of the eye and not to the human visual system's performance with specific types of tasks. Actually, however, the eye can detect visual stimuli as small as one second of arc, with approximately 14 seconds of arc being reliably reported under normal viewing conditions (the size of crosshairs on binoculars). But, detecting is different from resolving (identifying). The human eye, under ideal conditions, can resolve details as small as 0.30 seconds of arc. However, the eye is not an ideal optical system and does not normally view stimuli under ideal conditions. For this reason, the normalized value of one minute of visual arc is commonly accepted as the minimum resolvable limit of the eye. But, this value is invalid unless the operational and environmental conditions to which it is to be applied are specified.

The eye has no well defined single limit of total image size that can be perceived as most other imaging systems do. Instead, there is a very small area of maximum resolution known as the fovea which covers a visual angle of approximately two degrees in any direction from the visual axis. This area is surrounded by an area of rapidly decreasing resolution, extending out to fairly wide angles (35-40 degrees). It is consequently necessary for the eye to scan from one fixation point to another in order to resolve an image larger than that which is included in the four degree central cone. The requirement to scan, in turn, limits the amount of information that can be presented at one fixation point, as the amount of detail

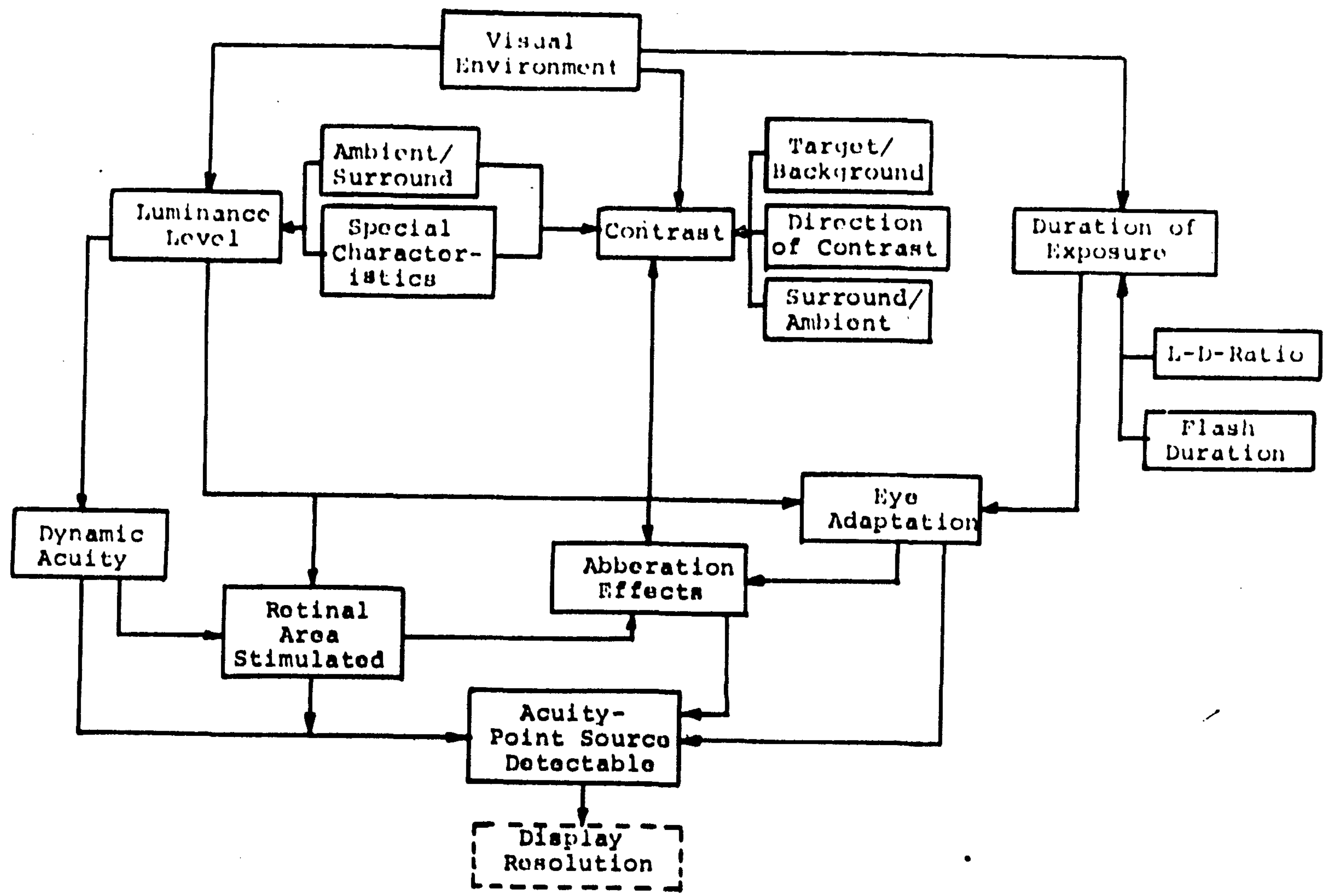


Figure 89. Factors Affecting Visual Acuity.

resolved is a function of viewing time. In a given unit of viewing time, the detail that can be resolved may be increased (or decreased) by varying the luminance output of the display (target, surround and background), contrast (both hue and brightness), and the adaptation level of the eye. The latter three parameters, in turn, interact to influence the aberration effects of the eye itself (spherical and chromatic).

A basic understanding of the parameters affecting visual acuity and an appreciation of the interaction of these parameters allows greater freedom for the display designer. If it is remembered that any information display consists of both the electronic flight display equipment and the visual system of the observer, and that the visual system limitations will limit the total system performance just as much as will the display equipment resolution, then judicious trade-offs can be made among the display parameters to optimize use of the observer's visual acuity. Evidence of the lack of this understanding is found in the fact that displays have been built with resolution greater than the eye can appreciate (high resolution CRT-type displays). Conversely, displays have been built which have actually degraded the observer's visual abilities (early first generation color CRT's). The task at hand then, is to relate the data from the area of visual acuity to the researcher in the area of display resolution; but it must be related in a manner that comprehendable to both areas. Once this 'communication gap' is bridged the road will be opened for more fruitful and efficacious exploration of both areas

The basic visual acuity factors to be examined include:

1. Luminance level - The effect of varying the background, target or surround luminance level while holding other factors constant.

2. Contrast ratio - The effects of varying hue and brightness contrast on visual acuity.

3. Viewing time - How viewing time affects the above factors.

4. Adaptation level - How the level of eye adaptation interacts with luminance level and contrast to affect acuity.

5. Aberration Effects - How the above factors interact to degrade visual performance.

6. Dynamic Acuity - What the effects of target and/or observer motion are on basic acuity.

7. Retinal Image Location - The effects of varying viewing angle and retinal image location on acuity.

Although these factors are examined individually, it must be remembered that they are not isolated linear functions. All of the above factors are interrelated and one cannot be addressed without considering it's effects on other parameters. The interaction of factors is more important, as far as visual acuity is concerned, than the range of variation of any single parameter. It must also be remembered that most of the data presented here were derived from studies conducted under 'ideal' or laboratory conditions; the greater percent of which used white light to illuminate dark symbols viewed against light backgrounds. Few, if any, of the performance deteriorating environmental factors (vibration, stress, visual fatigue) were present. Consequently, the data presented are for 'ideal' conditions. With the exception of one or two studies, little experimentation has been done under actual 'operational' conditions (Figure 89).

LUMINANCE LEVEL

Visual acuity varies directly as a function of the luminance level of the display being observed. Luminance level also interacts with a number of other display parameters (contrast ratio, eye adaptation, emitted hue, and aberration effects) to indirectly affect acuity. This interaction effect will be addressed later in this section. First, however, the two primary display luminance sources will be discussed; display background luminance and display surround illumination.

Background Luminance

The curve in Figure 90 is an average drawn through the data from six separate investigations of visual acuity as a function of display background luminance. These data are derived from foveal viewing of light targets on uniformly illuminated white backgrounds. It is seen that visual acuity increases rapidly as the luminance increases in the middle range of values (from 0.01 to 100 millilambert or log = -2 to log = 2). Above this point, the curve does not rise as rapidly, although it continues to increase.

Luxenberg and Kuehn (Ref. 226) report a study conducted by Lythgoe (Ref. 227) in which the Landolt Ring was used at varying orientations to obtain visual acuity data as a function of luminance level. The results of this study are plotted in Figure 91. The target (dark) was viewed against a white background and the entire visual field (with the exception of the highest luminance level) was kept approximately equal to the background. The observer's eyes were adapted to each luminance level prior to measurement and the criterion for the determination of the opening location was taken as nine correct responses out of 16 trials.

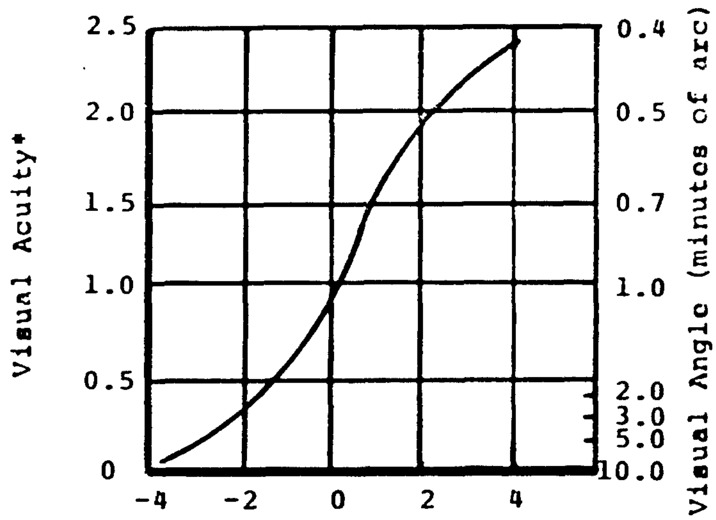
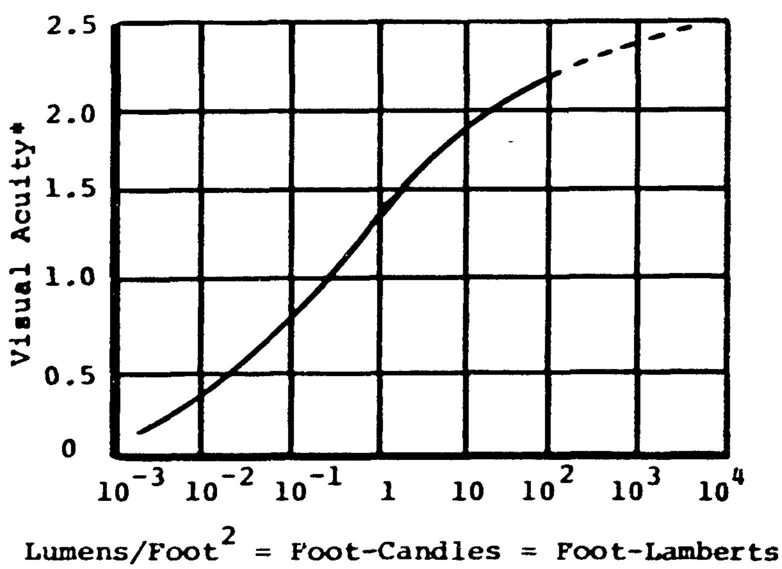


Figure 90. Visual Acuity as a Function of Background Luminance. (After Moon and Spencer, Ref. 245).



* Operationally defined as reciprocal of the angle in minutes of the smallest resolvable detail.

Figure 91. Acuity as a Function of Background Luminance. (After Lythgoe, Ref. 227)

Hecht and Mintz (Ref. 161) reported a study in which they measured visual acuity as a function of different illumination levels. Their results indicated that the highest illumination level (100 FL-L) produced visual acuity fine enough to detect stimuli as small as 0.5 second of arc. This finding is particularly interesting in light of the fact that microscopic studies (Ref. 269) have shown that individual rod and cone elements are much larger than this. They are, in fact, approximately 30 seconds of arc (1.5 to 2.5 microns). Morgan and Stellar (Ref. 248) have attempted to explain this phenomena by pointing out that the actual pattern of the stimulus on the retina is many times the size of the visual object that can be seen. Light passing through the eye diffracts in the ocular media so that the image in the retina is a somewhat enlarged and distorted version of the original stimuli. The authors suggest that a stimulus on the order of 0.5 seconds of arc may stimulate as many as three or four cones.

Geldard (Ref. 130) suggests that both rods and cones vary among themselves with respect to threshold. At the lowest illumination levels, only a few rods are stimulated. Since these rods probably have a chance distribution, this amounts to a sparse functional population of rods resulting in a "grainy" image. As light intensity increases, more and more rods have their thresholds passed, bringing a greater number into play and consequently reducing the average distance between functional receptors and the apparent grainy effect. At a certain point (acuity of approximately 0.1 mm) cone threshold is reached and the cones replace rods as functional receptors. At this point, vision is best foveally and improves steadily with increasing illumination. Only when the threshold of all the cones have been passed will further increases in illumination be ineffective in increasing acuity. If the illumination is excessively high, all the cones are stimulated maximally due to the reflectance and this results in "glare".

The data presented in Figure 92 were compiled by Chapanis (Ref. 62) and shows the effect of background luminance over a range from 0.0001 Ft. L. to 100 Ft. L. As Chapanis pointed out, the two graphs compare favorably at the low luminance ends, however, agreement is missing at the upper luminance ends. This fact could almost be predicted from the two experimental methods used. The data on the left were obtained from long exposure times (three seconds or more) while the data on the right were obtained from short exposure periods (0.17 second per exposure). As is seen in the section on viewing time, visual acuity is a function of viewing time. Even with the experimental difference and the differing results, these graphs tend to indicate the trend visual acuity follows as the background luminance is increased.

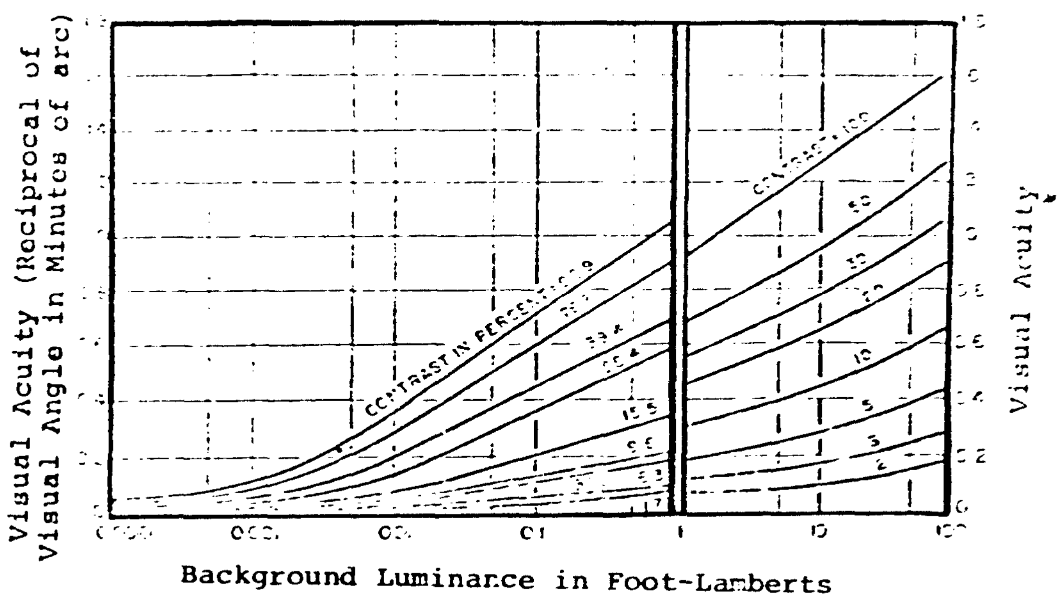


Figure 92. Visual Acuity as a Function of Background Luminance and Luminance Contrast. (Adapted from Refs.62, 75, and 86)

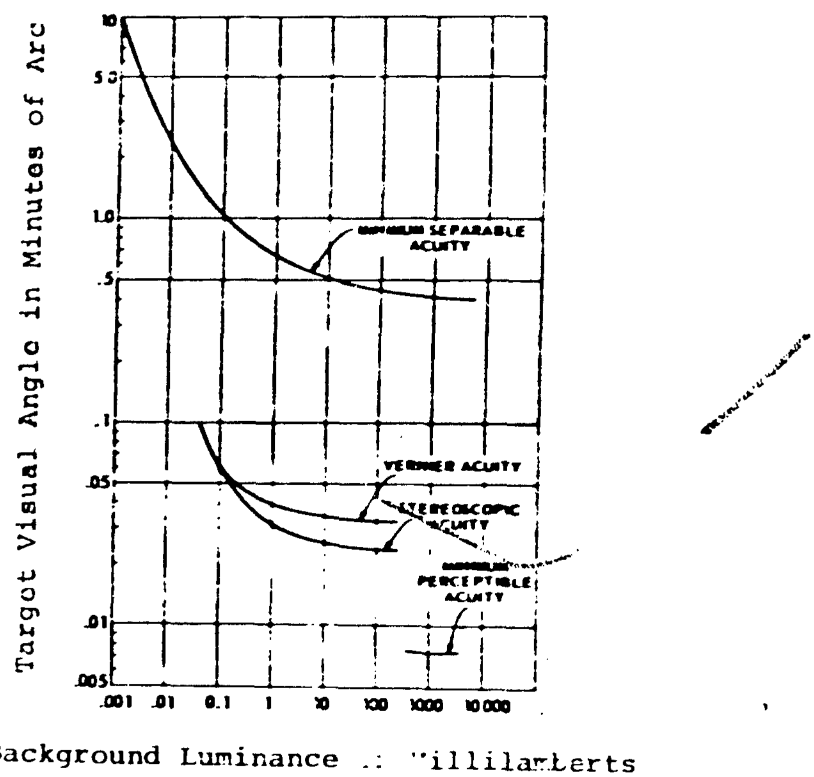


Figure 93. Minimum Visual Angle as a Function of Background Luminance. (Adapted from Ref. 4-6)

Figure 93 indicates the effects of background luminance on the different types of visual acuity. As is seen in this figure, minimum separable acuity is most influenced by increasing the background luminance. The data presented in this figure were collected from a number of sources (Ref. 286) and indicate the relationship of the different types of acuity as well as the general ranges for each. It is noted, however, that the data were collected by studies using widely varying experimental methods, limited subject populations, limited luminance ranges and in some instances different measurement techniques (Ref. 245). The data are, however, useful in predicting trends in acuity as a function of acuity.

There appears to be a decisive lack of concrete data relating visual acuity to background luminance as a function of the many display variables associated with electronic flight displays. A comprehensive multi-parametric examination of this function appears warranted in light of the many unique and as yet unexamined parameters found in airborne electronic displays. Until these desired data are obtained, however, the trends present in the above reported studies may serve as a guide. Careful evaluation of all the electronic display parameters expected to affect acuity must also be conducted in examining acuity as a function of background luminance (brightness contrast, hue contrast, size of target and display, ambient illumination levels, eye adaptation level, etc.) for electronic flight displays.

Surround Luminance

The display surround illumination level (luminance of area immediately around display and extending outward in visual field) has a significant effect on visual acuity and the visibility of targets in the display itself. In an early study, Cobb (Ref. 73) confirmed his earlier work with Geissler (Ref. 74) by showing that both contrast sensitivity and visual acuity depend significantly upon the surround-to-background brightness ratio. The above authors found that as the ratio rose above unity, the visual threshold rose rapidly and to a large extent; and as the ratio dropped below unity, the threshold also rose, but much more slowly and over a more limited range. The smallest visual acuity values were found at or near surround-to-background ratios of one. In their experiment, Cobb and Geissler used a rectangular test patch which subtended a visual angle of 1.5 degrees by 2.25 degrees at the eye and which was viewed from a distance of 28 inches. To measure contrast, the rectangles were divided in half, each half differing in brightness. One half remained at a constant brightness, while the other half was varied to determine threshold. For the visual acuity determination, both halves were adjusted to the same brightness and served as the display background. The brightness of this background was varied with the brightness of a larger (3 ft. by 3 ft.) surround to arrive at the surround-to-background ratios,

while two black parallel bars provided the critical detail which the four subjects had to discriminate. In all cases the outer edges of the background field coincided with the inner edge of the surround field.

Lythgoe (Ref. 227) examining the effects of the greater surround on acuity, conducted a study with considerably more detail. He used black Landolt rings as targets with outside diameters varying from 2 to 30 min. of arc (0.4 to 6.0 min. of arc gaps). The Landolt rings were centered on 1 degree by 2 degree white rectangular backgrounds illuminated with 12.6 Ft. Lamberts of illumination. Surround brightness was varied from 0.0 to 38.1 Ft. Lamberts. His results indicated that varying the surround brightness from 0 to 1/100 or 1/10 of the background brightness progressively increased visual acuity while further increases in surround brightness to the level of background brightness caused a slight drop in acuity. A very pronounced drop in acuity occurred with further increases in surround brightness (Figures 94, 95, and 96).

In 1926, Holiday (Ref. 169) provided experimental data concerning the effect of point source of glare on target visibility as a function of background size and brightness. He then related these data to the effects of surround-to-background brightness relationship (for extended surround) by means of a prediction equation. The principle points of his findings were:

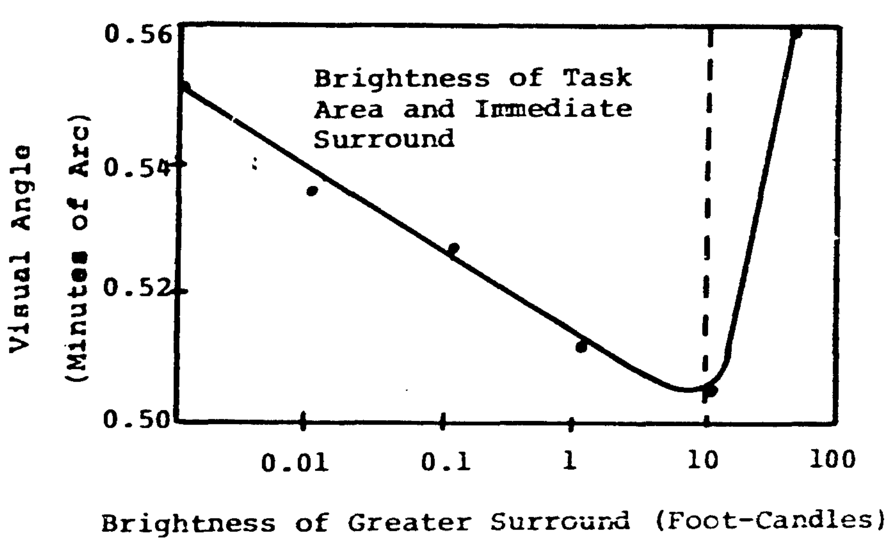
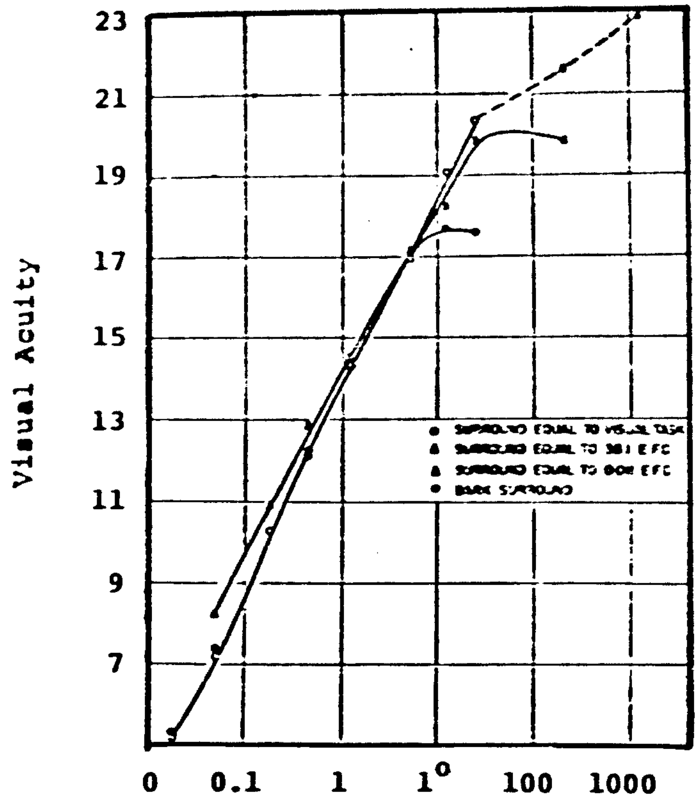
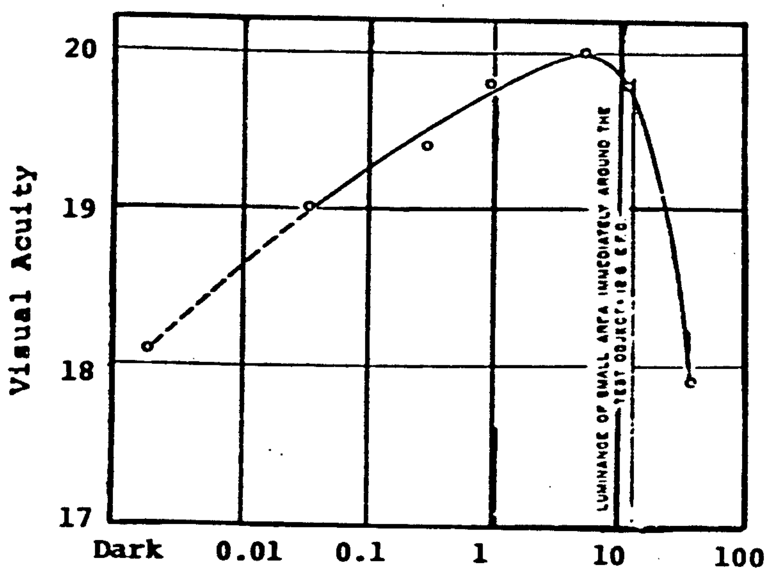


Figure 94. Threshold Visual Angle as Determined by Brightness of Greater Surround. (After Lythgoe, Ref. 227)



Luminance of Small Area Immediately Around Test Object
(In Equivalent Ft. Candles)

Figure 95. Acuity as a Function of Luminance of Immediate Surround. (After Ref. 227)



Luminance of Larger Surround Area in Equivalent Ft. Candles

Figure 96. Acuity as a Function of Surround Luminance With Small Area Luminance Held Constant. (After Ref. 227)

1. The effects on acuity of multiple sources of glare are additive; that is two or more glare sources having the same angular separation from the visual axis have the same effect on contrast sensitivity as a single glare source placed at the same angular distance, provided the latter produced the same illumination at the eye as the former two sources.

2. The glare source produced an effect on contrast sensitivity proportional to the illumination it produced on the eye and approximately inversely proportional to the square of its angular separation from the line of sight to the target.

3. Any effect from a glare source could be duplicated by substituting a veiling illumination of suitable brightness on the rest of the visual field. This factor led Holiday to conclude that the eye's adaptation level resulting from the glare source was the controlling factor and that glare effects could be measured and specified by determining the equivalent brightness of the background (filling the remainder of the visual field) that had the same effect as the glare source on the eye's contrast sensitivity.

From the above, Holiday reasoned that a uniformly lighted bright surround could be considered an infinite number of tiny glare sources, each emitting the same luminous flux per unit area as the uniform surround. Based on these conclusions, he proposed an integrated formula for the computation (for a given surround-background relationship) of the adaptation brightness of the eye (full field brightness necessary to yield the same contrast sensitivity). With this 'adaptation brightness' calculated, one can refer to experimentally determined target contrast threshold versus background brightness curves without glare to find the contrast required for threshold detectability under those surround conditions.

Moon and Spencer (Ref. 245) completed the mathematical expression of the relationship proposed by Holiday. In their version for a circular surround brighter than the circular background (1.0 degrees visual angle), the factor (BA/BB) by which background brightness must be multiplied to obtain the equivalent adaptation level of the eye is:

$$BA/BB = (1.006 - 0.0006 \frac{BS}{BB}) - 0.0192 \ (1 - \frac{BS}{BB}) \ Q$$

where: $Q = \dfrac{\sin 2\theta_1}{2\theta_1} - C_i \ (2\theta_1)$

BA = equivalent adaptation brightness
BB = background brightness
BS = surround brightness
θ_1 = angle between visual axis and inner border of surround (where $2\theta > 1.5^{\circ}$)
C_i = the cosine integral

This formulation assumes that the outside diameter of the surround subtends at least 114.0 degrees (2 radians), beyond which the effects are considered negligible. Little (if any) direct verification of this prediction equation have been performed. Ireland (Ref. 179) suggests that some of the individual assumptions on which it is based, however, have been tested (Refs. 255 and 325).

Ireland conducted a study to experimentally examine the validity of the Moon and Spencer's prediction equation (which had not been done prior). Projected Landolt Rings subtending a visual angle of 9.65 min. of arc with gaps subtending 1.93 min. of arc were used in the experiment and the target brightness were varied (0.1 to 0.7 log units) with exposure time limited to 1.0 second. The subject's eyes were 89 inches from the background screen. Subjects were instructed to depress one of eight buttons corresponding to the location of the detected Landolt Ring gap. Table 57 summarizes the experimental background-to-surround ratios used in the study.

Figure 97 indicates that the threshold increases with increases in the surround brightness-to-background brightness ratio above 10:1 (log = 1/1 = 0). All thresholds for BS/BB ratios of 57:1 and 100:1 were higher than those obtained from smaller ratios, and all differences were statistically significant. This figure also indicates a slight tendency for the threshold to increase as the BS/BB ratio decreases from 1:1 to 0:1, although the decrease was not significant. Ireland concludes from the data that:

1. For surrounds brighter than the background, the contrast threshold is fairly sensitive to the surround-to-background ratio and that the increase in a subject's contrast threshold appears to be proportional to the increase in the surround brightness. This appears to conform to Holiday's findings with point-glare sources whose effect also appear to be proportional to their brightness. The following formulation is suggested for threshold contrast of a given background brightness, with surround-to-background ratios greater than one:

$$C' = C_{ref}(0.9815 + \frac{0.0185\ BS}{BB})$$

where: C' = threshold contrast for a given ratio, $\frac{BS}{BB} > 1$

C_{ref} = threshold contrast when BS/BB = 1

BS = surround brightness

BB = background brightness

Table 57. Experimental Background and Surround Brightnesses and Corresponding Surround-to-Background Brightness Ratios. (Adapted from Ireland, Ref. 179)

MAIN EXPERIMENT

BB	BS (mL)	$\frac{BS}{BB}$ (nom:0)	BS (mL)	$\frac{BS}{BB}$ (nom:1)	BS (mL)	$\frac{BS}{BB}$ (nom:10)	BS (mL)	$\frac{BS}{BB}$ (nom:100)
.17	0	0	0.14	0.82	1.45	8.53	16.14	94.94
1.57	0	0	1.45	0.92	16.14	10.28	176.18	112.2
18.43	0	0	16.14	0.88	176.18	9.56	1049.	56.9

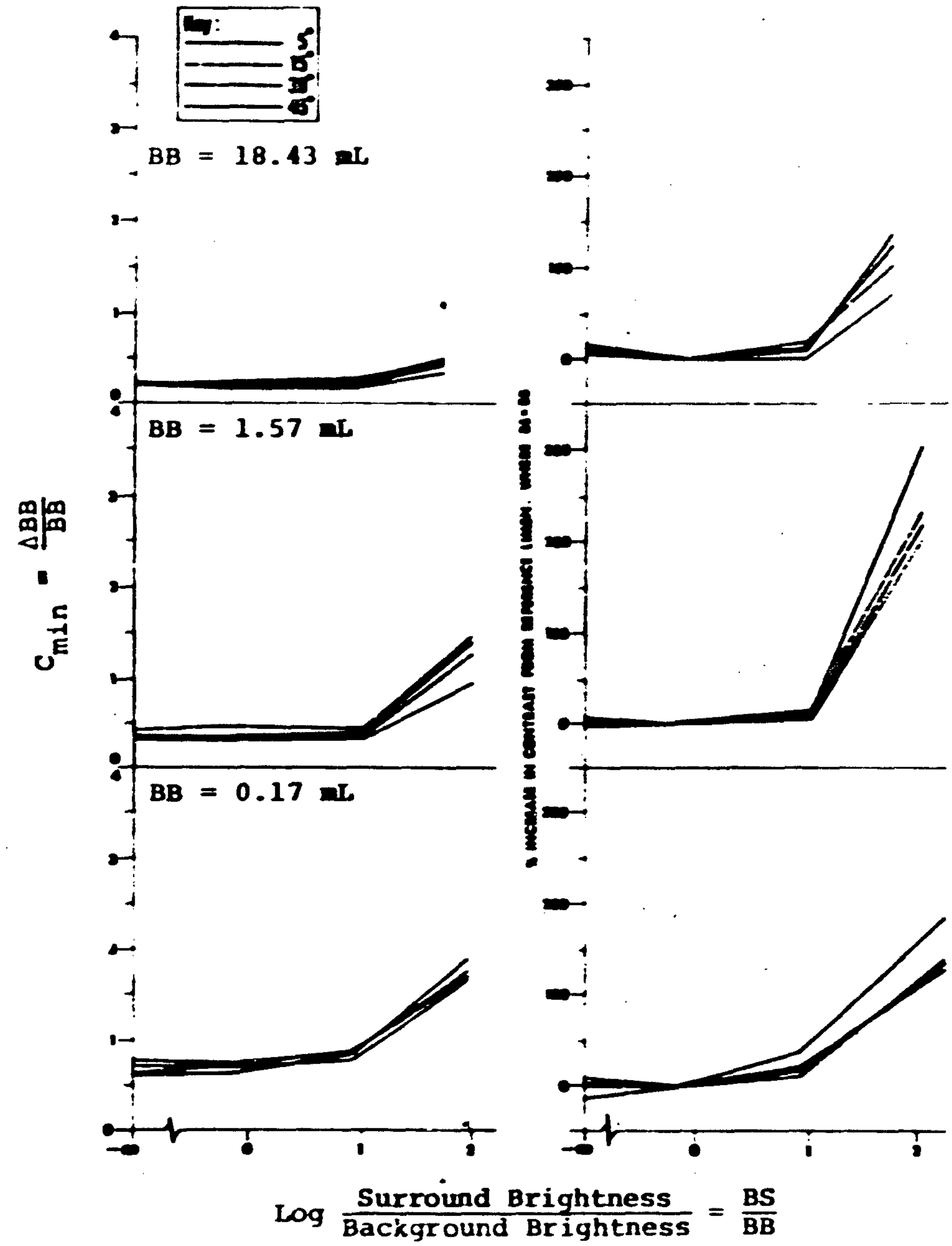


Figure 97. Effects of Various Surround to Background Luminance Ratios. (After Ireland, Ref. 179)

2. The results indicate that surrounds considerably darker than the background may also adversely affect visual performance (raises the threshold). Visual acuity is reduced progressively with increasingly darker surround.

3. From a practical standpoint, the results of this experiment establish a basis for the specifying of increased display contrast requirements when the area surrounding the display is substantially brighter than the background of the display.

In general visual acuity is best when the eyes of the observer are adapted to the brightness level of the display background. However, acuity is reduced when the eyes are adapted to the background and the background brightness is lower than the brightness of the greater surround brightness. Likewise, a reduction in acuity is experienced when the background brightness is considerably brighter than the general surround brightness.

EFFECTS OF CONTRAST

Luminance contrast, which is the measure of how greatly the target luminance (B_t) differs from the background luminance (B_b), directly influence the minimum visual angle of a target that can be detected. This relationship is expressed by the following ratio devised by Blackwell (Ref. 32) and is plotted in Figure 98.

$$C_B = \frac{B_b - B_t}{B_b}$$

Contrast can vary from zero to 100% for targets darker than their background and from zero to infinity for targets lighter than their background. This relationship can in turn be directly influenced by the amount of ambient illumination incident to the display surface (see section on contrast), absorption-reflection characteristics of the display surface, the symbol and background luminance emitted by the display itself, the hue of the emitted luminance, the eyes adaptation level and several other lesser considerations. In general, however, the higher the contrast ratio at a given background luminance level, the smaller the target size (measured in minutes of visual angle subtended) that can be detected. Figure 98 is the classical graphical presentation of this relationship (from Blackwell, Ref. 32). The discontinuity apparent at about the 0.003 millilambert position marks the transition from rod to cone vision.

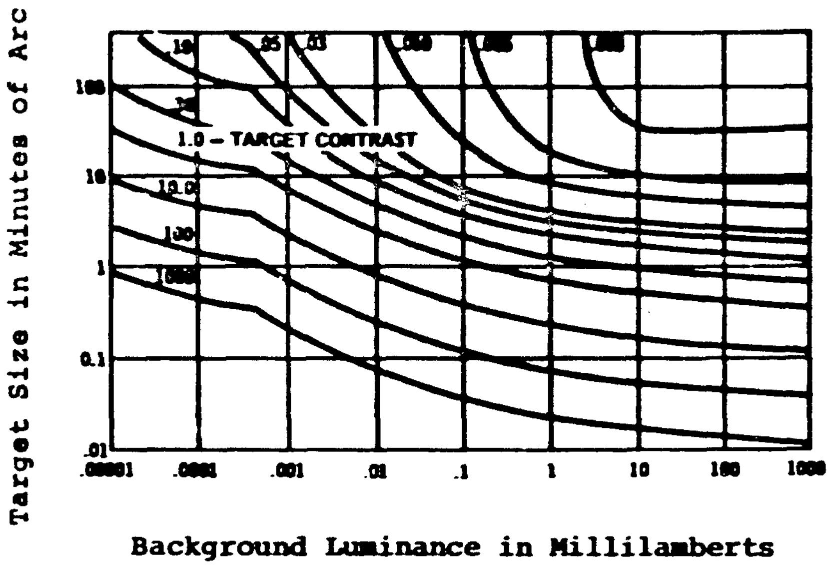


Figure 98. Minimum Detectable Target Size for 50% Probability of Detection as a Function of Background Luminance and Target Contrast. (Adapted from Refs. 32 and 232)

It must be pointed out that the information presented in Figure 98 are the data for 50% probability of detection. In most practical situations, a higher probability of detection is required (95-100%). This value can be estimated by multiplying the contrast ratio for the 50% threshold data by three (Ref. 58). Additionally, these data are for minimum perceptable size and not for minimum separable. No valid data are available for minimum separable values as a function of contrast. It should be remembered that the values derived from these conversions are "rules of thumb" only and not precise values.

Figure 99 presents somewhat similar data for luminance contrast thresholds presented in a different format. In this presentation, variations in the luminance contrast threshold (Δ B/B, where B is luminance) are shown as a function of background luminance and target size. (Pupil diameter is indicated as it varies with luminance level). Two distinct relationships can be observed in this figure:

1) As the background luminance is reduced, the visual target must be a great deal darker or lighter than their background to be detected.

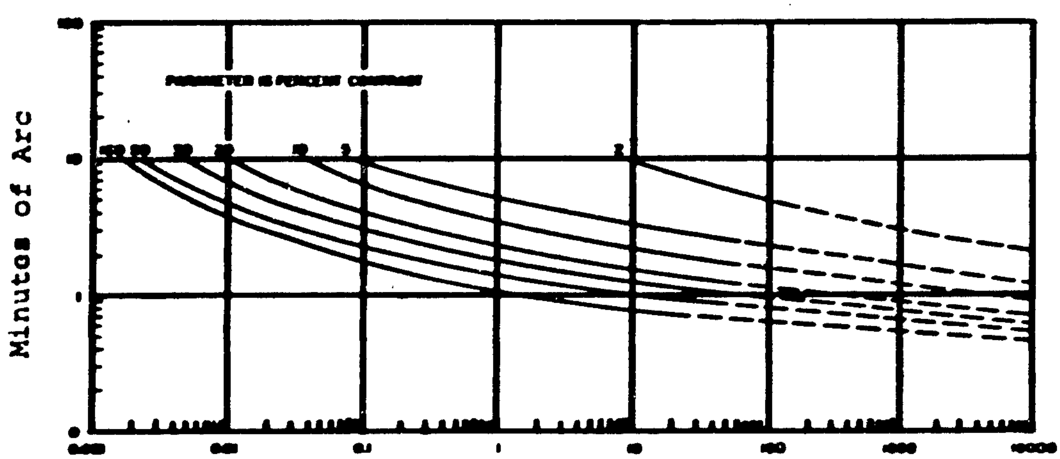
2) At any given luminance level, smaller objects must have greater contrast than larger objects to be equally detectable.

The data presented in this graph were derived from subjects with knowledge of target location prior to exposure of the target and the exposure times themselves were varied (0.05 to 0.5 sec.).

Figure 99 also indicates that acuity is affected by contrast and background brightness. Carel (Ref. 58) suggests that in the case of skeletal displays (HUD type displays or outline VSD displays), the requirement is not only that the thin line elements be visible, but that read-out accuracy be maintained by requiring that the separation between two elements be visually resolved when the separation is equal to a line width. For this reason, Carel suggests that the information contained in these graphs be used to estimate the minimum required brightness and contrast for electronic displays.

DIRECTION OF CONTRAST

It is worth noting that there is a distinct difference between the smallest bright target on a dark background that can be detected and the smallest dark target on a bright background that can be detected. Figure 100 indicates the effect of direction of contrast on the ability to discriminate bars. The measure of resolution used is the smallest distance two bars could be separated and still be seen as separate. It is observed that as the level of retinal illumination increased beyond approximately 3.2 photons (0.5 log units or .34 millilamberts with pupil diameter = 2 mm), the eyes ability to discriminate between the two bars deteriorated instead of improving, for the



Background Luminance in Foot-Lamberts

Figure 99. Visual Acuity as a Function of Contrast. (After Carel, Ref. 58)

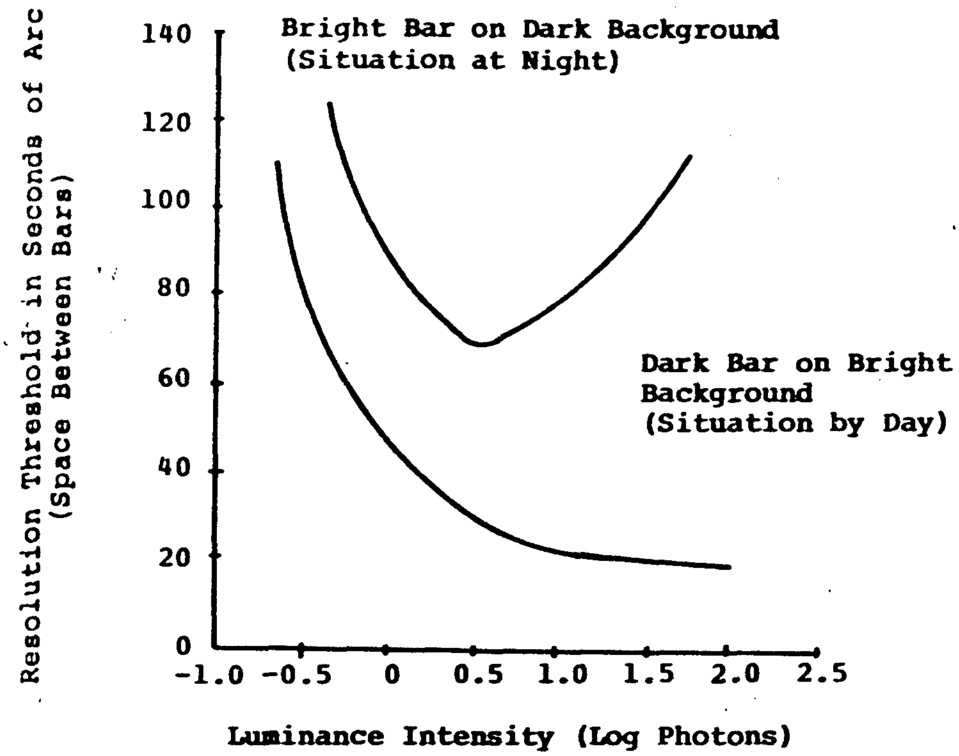


Figure 100. Acuity as a Function of Direction of Contrast. (After Wilcox, Ref. 354)

brighter bar against the dark background. However, with dark bars on light background, acuity continues to increase with increasing luminance.

There are data indicating that dark targets considerably smaller than those plotted in the above graph can be detected. Hecht, Ross, and Mueller (Ref. 160) produced data indicating this and also indicating that the shape of the target affects the minimum size that can be detected. They suggest that a thin wire with a diameter of 0.51 second of arc and a length of 60 minutes of arc can be seen silhouetted against a sky of about 2,000 Ft. Lamberts 95% of the time, whereas a dark square silhouetted against the same sky must be only 18 seconds of arc on each side to be seen 95% of the time. The authors remarked that the square is more efficient as a target since the total angular area of the square is only one-third that of the wire.

Figure 101 shows the effect of the area of a rectangular stimulus on threshold contrast (B/B) for 5 ratios of length to width of rectangles. Generally, with large areas, threshold contrasts for fixed areas decreases as the shape approaches a

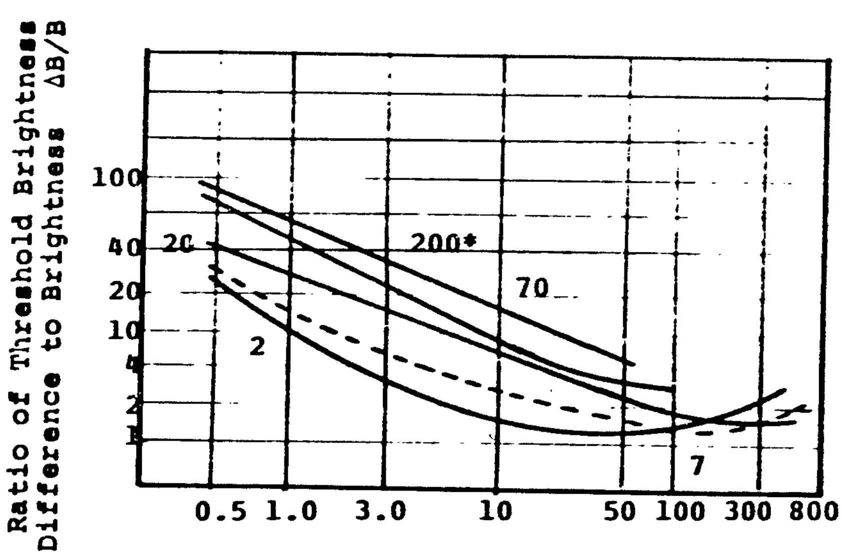


Figure 101. Contrast Threshold as a Function of Area of Stimulus. (Adapted from Wulfeck, Ref. 363)

*Indicates Length/Width Ratios of Figures.

square. When the total angular area of the target approaches 100 min^2, shape becomes unimportant as a determinent of minimum detectable size. The data presented in Figure 101 are for 75% probability of detection of a dark target against a light background.

Baker and Grether (Ref. 12) state that there is no known lower limit of visual angle for bright targets against a dark background (similar to night viewing conditions). They state, for example, that the Star Mira is clearly visible at night and that it subtends a visual angle of only 0.056 second of arc.

McLean (Ref. 231) conducted a study to examine the effect of color contrast versus brightness contrast, brightness contrast values, and contrast direction. Twenty-four visually screened subjects viewed three inch diameter dials at a distance of 18 inches. The dials were mounted on cardboard and illumination on their surface measured 32 Ft. Candles. Each subject viewed 78 dials (6 practice and 72 experimental) with each card having one of the 72 possible color combinations on it. Pointer position, contrast value and contrast direction were counter-balanced. The task required rapid and accurate identification of the pointer position.

The results of this study indicate that the effect of color contrast and brightness contrast are dependent upon the direction of the contrast. The light-dark contrast direction apparently facilitates the legibility of color contrast combinations relative to brightness contrasts (Figure 102). Conversely, brightness contrast is superior for the dark-light contrast direction.

The direction of contrast is also an important factor in the detection of fine detail in visual targets. Schmidt (Ref. 290) plotted typical examples of fine detail detection (Figure 103) giving visual acuity limits for targets either brighter or darker than their backgrounds for different background luminance conditions. These curves allow predictions of estimated visual acuity for the discrimination of the shape of targets of known luminance on a background of known luminance, to the luminance to which the eye of the observer is adapted. The visual acuity values listed correspond to the visual angles subtended by the critical detail which was required for the distinction of a square from a circle of equal area, but when size was varied.

It is seen in the above discussion that display contrast (and the direct of contrast) is a prime consideration in the determination of visual acuity. In general (with other factors held constant), the higher the contrast between the visual target and the display background, the smaller the visual angle required for detection and identification of detail. At low luminance levels, bright targets on dark displays generally produce greater visual acuity, while with high luminance levels (daylight conditions) dark objects on light backgrounds produce greater acuity. The display background luminance is less important in

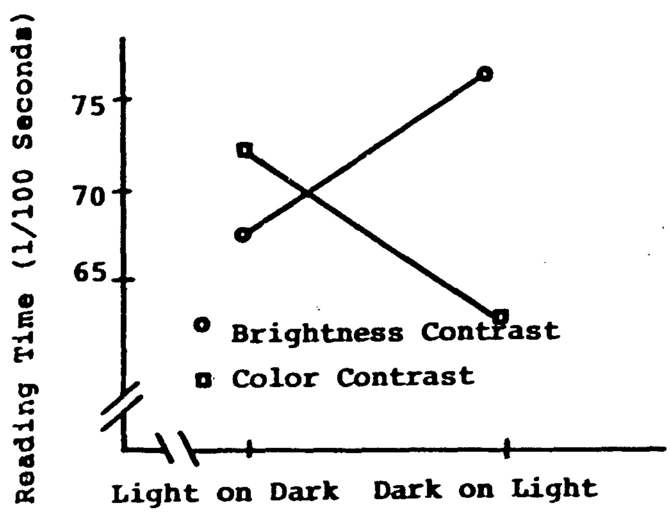
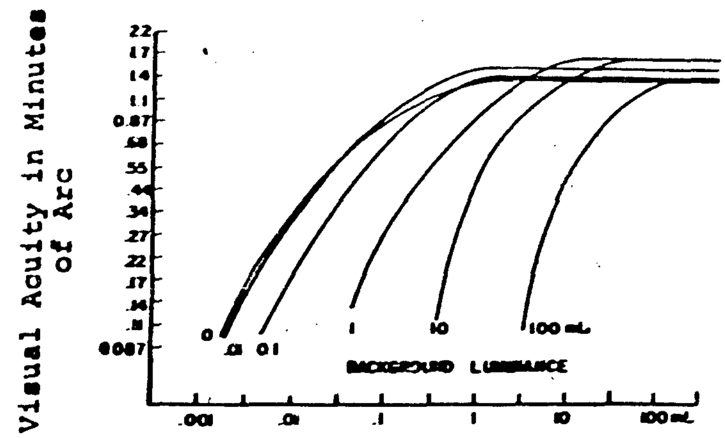
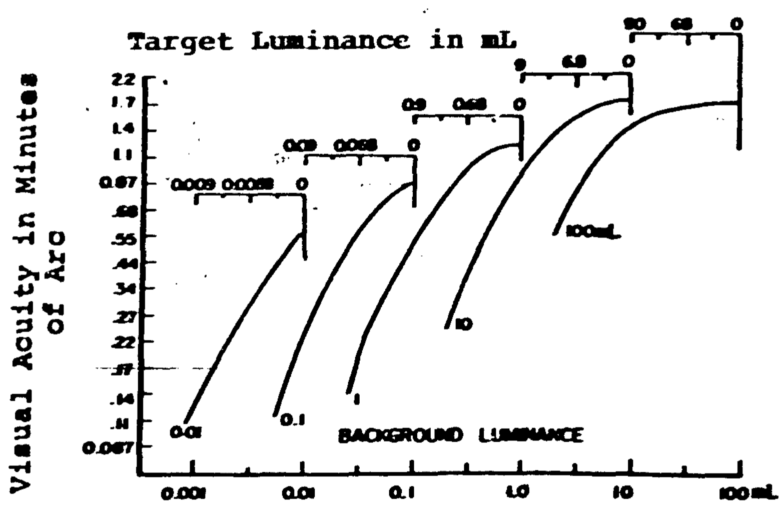


Figure 102. Effects of the Interaction Between Color and Brightness Contrast with Direction of Contrast on Reading Time. (After McLean, Ref. 231)



Difference Between Luminance on
Background and Target

a. Target Brighter than Background



Difference Between Luminance of
Background and Target

b. Target Darker than Background

Figure 103. Visual Acuity as a Function of Target and
Background Luminance. (After Schmidt, Ref. 290)

determining visual acuity than the contrast between the background and the target. For contrast ratio recommendations, see section on legibility contrast requirements.

The above recommendations and findings were based on studies conducted with white light under laboratory conditions. Additionally, in most instances, small subject populations were used and consequently little reliability can be expected between studies. The early work by Blackwell in the area of contrast has prevailed for a quarter of a century with little in the way of validation studies being performed. In light of current display technology (high-luminance emission, multi-colored, high information density computer assisted) the feasibility of generalizing these earlier low-light level achromatic data to the newer generation of displays must be questioned. It is time for a new series of studies on contrast utilizing current display technology and conducted under airborne operational conditions.

EYE ADAPTATION LEVEL

The smallest visual detail that can be instantaneously resolved upon viewing an electronic display is a function of the adaptation level of the eyes of the observer at the time of viewing the display. A number of factors interact to affect this adaptation level and include:

1. The duration of the exposure to the pre-adapting luminance.

2. The average intensity of the pre-adapting luminance.

3. The size, shape, contrast condition and viewing time of the object being viewed.

4. The spectral characteristics of the pre-adapting luminance and the emitted luminance of the display.

5. The foveal area stimulated by the visual target.

6. Individual differences among observers.

When the eyes of the observer have been adapted to the luminance level of the surround (ambient illumination level) and then are fixated on a less bright (darker) display surface, the luminance level that is just visible upon viewing the display is defined as the instantaneous threshold. Figure 104 graphs the instantaneous threshold as a function of the pre-adapting luminance. It is observed that the curve is relatively straight

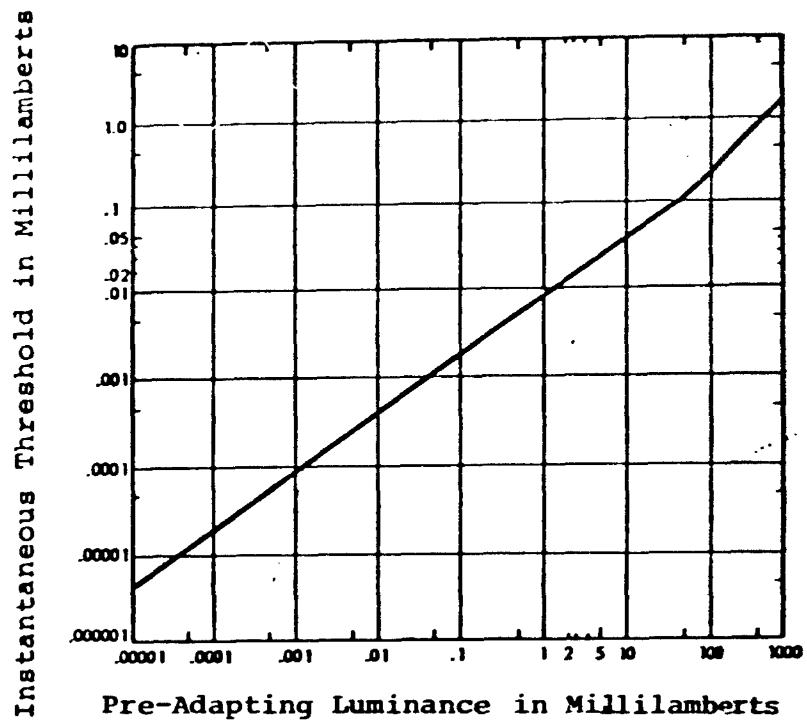


Figure 104. Instantaneous Threshold as a Function of Pre-Adapting Luminance Level. (After Nutting, Ref. 256)

except at the higher luminance levels where factors other than adaptation are present (glare-effect, aberration, pupil enlargement). These data were collected using a black square subtending a visual angle of 10 minutes and viewed against a light background. The eight subjects were pre-adapted to the indicated luminance level (time period not specified) prior to exposure to the test targets. The data are for simple light detection tasks and as a consequence do not permit a prediction of the instantaneous visual acuity threshold, which would require the discrimination of form. An approximate 100 to 1 ratio exists between pre-adapting luminance level and the instantaneous threshold level. For example, an observer adapted to a luminance of 1.0 mL can see a 10 minute square target about 100th as bright immediately after the pre-adapting luminance is turned off.

Exposure of the eyes to relatively high brightness levels for approximately 2.5 minutes will produce, for all practical purposes, a "steady-state" of adaptation to that level. This in effect, means that longer periods of pre-exposure to the higher luminance levels will have little further effect on the immediate sensitivity of the eye. Shorter periods of pre-exposure, however, affect the sensitivity of the eye proportionately less. Figure 105 indicates this relationship. For any

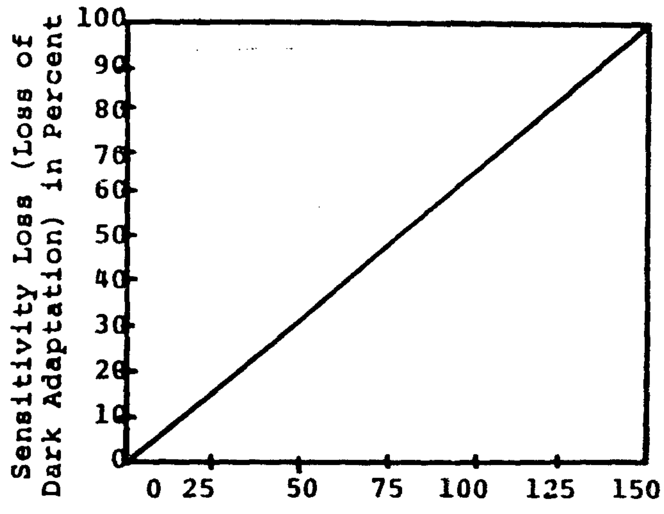


Figure 105. Rate of Loss of Dark Adaptation after Exposure to Light. (Adapted from Mote and Riopelle, Ref. 249)

given pre-exposure duration, the value of the ordinate is used as a multiplier of the exposure brightness to give the steady-state adaptation level of the eye. For example, if the eye is exposed to 2,000 millilamberts (approximate daylight brightness) for 15 seconds, the eye has a sensitivity loss equivalent to that of being exposed to 200 millilamberts (15/150 x 2,000 mL) for 150 seconds or more. These adjusted values then can be used with Figure 104 to obtain an estimate of the instantaneous threshold. The values derived from this graph will be approximations only.

Not only does the period of pre-adaptation affect the sensitivity loss, but it also appears to affect the rate of re-adaptation to the display luminance. Chapanis (Ref. 62) reports the results of a study by Haig (Ref. 152) which indicates that following a very short period of pre-adaptation to higher luminance levels, the rate of re-adaptation to the display luminance level is more rapid than with longer exposures to the pre-adaptation level (Figure 106). In other words, if the observer is completely adapted to the surround illumination level, a longer period of time will be required to adapt to the luminance level of the display, while if the surround adaptation is only partially accomplished, readjustment to the display luminance level will be much more rapid.

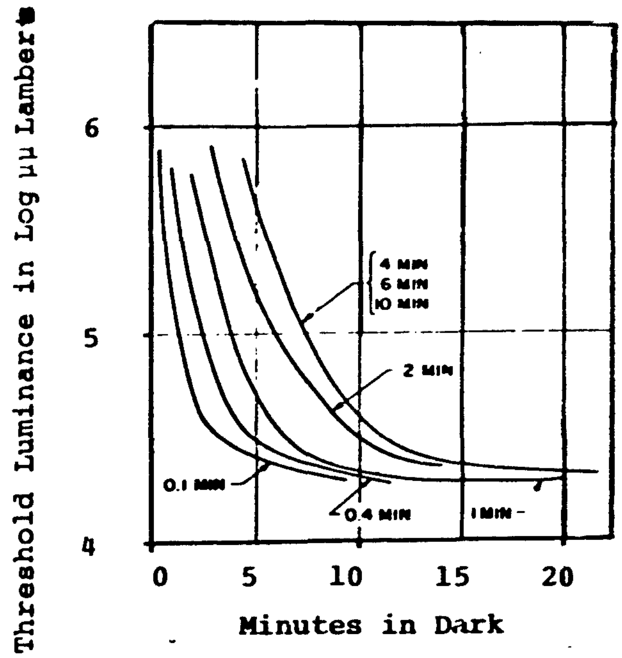


Figure 106. Adaptation as a Function of Pre-Adaptation Time. (Ref. 152)

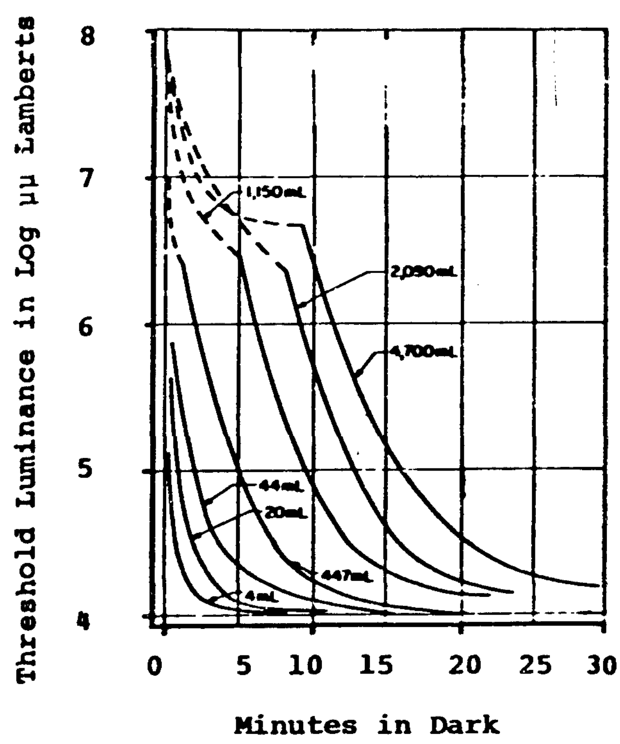


Figure 107. Threshold Luminance as à Function of Pre-Adapting Luminance. (Adapted from Haig, Ref. 152)

In terms of the visual acuity of the individual, the greater the adaptation period required:

1) The larger in size the target must be in order for it to be instantaneously detected (or identified), or

2) the longer the period of adaptation 'blindness' resulting from the inability to detect the smaller targets.

The data in Figure 106 above were obtained from a pre-adaptation luminance level of 447 millilamberts with pre-exposure periods ranging from 0.1 to 10 minutes. The data is from one subject viewing dark targets subtending 10 minutes of visual arc and viewed against a light background (luminance threshold determined by the method of limits. That is by starting stimulus intensity below threshold and increasing it until threshold is passed and vice versa). Unfortunately, this appears to be the only valid study examining this parameter.

The time required for dark adaptation decreases rapidly as the luminance intensity of the pre-adapting light is decreased. Chapanis (Ref. 62) reports a study conducted by Haig (Ref. 152) in which seven different levels of pre-adaptation luminances were used (4,700, 2090, 1150, 447, 44, 20 and 4 millilamberts) with exposure times of four minutes. The results of this study are presented in Figure 107.

Ketchell (Ref. 203) reports the results of a study by Craik (Ref. 92) in which the effects of adaptation level on acuity were studied. Craik used a 16 degree adapting field, a test field exposure period of 2 seconds, and a method of limits to determine the resolution threshold for a double-line test object of variable size. Test field luminance and eight adaptation levels used ranged from 0.001 to 10,000 Ft. Lamberts. Craik reported that acuity was best under conditions of approximate equality between adapting and test field luminance in the range of 10 to 10,000 Ft Lamberts. Acuity was reported to be considerably less when the test field (equivalent to display background) and the adaptation luminance level differ by 3 log units or more. It is observed in Figure 108 that when the test field and the adaptation level are equal, (10,000 Ft. Lamberts at point D) visual acuity is best. At point B and C (test field luminance of 100 and 1,000 Ft. Lamberts respectively), acuity is somewhat degraded and at point A (test field luminance of 10 Ft. Lamberts), visual acuity is severely degraded. From these results, Ketchel concluded that a ratio of 1 to 100 is the approximate limit between the test and the adapting field if the visual acuity is not to be seriously degraded. These findings are in general agreement with the findings of Hanes and Williams (Ref. 158) and is the ratio recommended by Baker and Grether (Ref. 12).

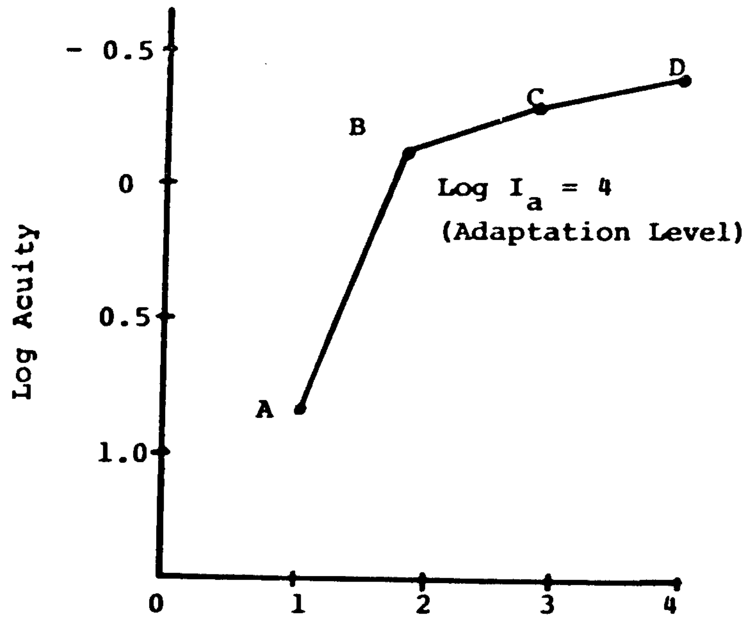


Figure 108. Acuity as a Function of Test Field and Visual Adaptation Level. (After Craik, Ref. 92)

Several limitations are found in the Craik study. One of these is that only two subjects were used in the study, and both of these suffered from slight myopia. Additionally, the study was restricted to a specific kind of acuity task (monocular separation of two metallic strips ranging from 0 to 40 min arc separation).

The usual procedure for tracing dark adaptation is to determine the dimmest light a subject can see at various times after the light has been turned out in a room. The data presented in Figure 109 are from a study conducted by Sloan (Ref. 311) and are representative of these functions. Sloan used a one degree white light situated in the nasal field of view (fixated 15 degrees from a fixation point). The solid line represents the average for 101 subjects. Two segments are discerned in this figure; an initial very rapid decrease in the threshold which levels off at about 10 minutes and a secondary adaptation which starts at about 10 minutes and continues for some period of time.

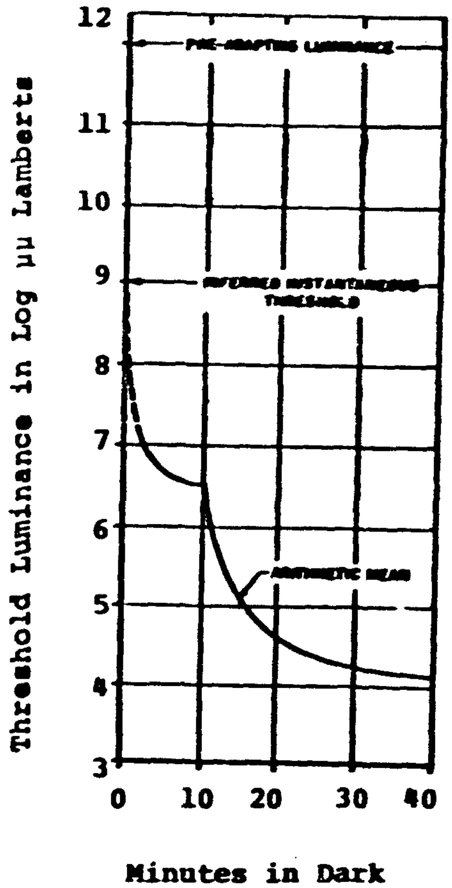


Figure 109. Instantaneous Threshold as a Function of Time in the Dark. (After Data from Sloan, Ref. 311).

The time required to adapt to a given threshold level is shorter when the pre-exposure luminance is lower and when the pre-exposure light is composed of light in the red portion of the spectrum.

Hanes and Williams (Ref. 158) conducted a series of studies which in part attempted to determine the effects of contrast ratios on instantaneous acuity. Four observers monocularly viewed a CRT display (using P7 phosphor) to determine the apparent threshold of pips in unknown locations after pre-adapting to seven different luminance levels. Two screen brightnesses were used in the study (0.001 and 0.22 millilamberts), and time was the measure of performance. The results of the study are summarized in Figure 110. The symbol subtended a visual angle of 1200 square minutes of arc. Detection time of five seconds constituted immediate detection (due to equipment lag time) and the figures represent 99% correct detection.

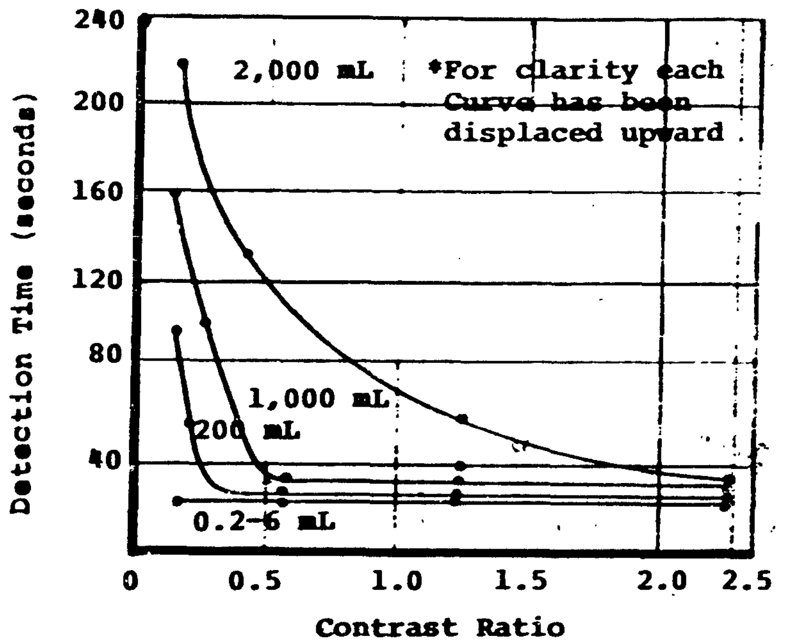


Figure 110. Time for Detection as a Function of Degree of Contrast (Test Field Brightness: 0.022 millilambert). (After Hanes and Williams, Ref. 158)

The conclusions that the authors (Hanes and Williams) drew from the results suggest that within the range of ordinary room illumination, the adaptation level of the eye is an insignificant factor. In fact, dark adaptation prior to viewing "rather bright" displays may be slightly harmful to target detection. Light adaptation up to a few foot candles may be slightly harmful when viewing a dimmer screen. It must be remembered, however, that these results were for normal room illumination and do not generalize to the much greater range found in the total operational spectrum for aircraft.

The size of the target to be detected on a display after pre-adapting to a higher surround illumination will in part determine the instantaneous threshold of the observer. The larger the target area, the lower the instantaneous threshold for detection, but also the greater the time required for total adaptation. Likewise, the smaller the target area (see Figure 111), the higher the initial instantaneous threshold luminance to be seen, but less overall adaptation occurs. Again, the period of rapid initial adaptation is observed, followed by a longer period of slower adaptation.

The spectral composition of the pre-adapting luminance will have a significant effect on the instantaneous threshold of an observer. As has been noted earlier in this section, the eyes are most sensitive to light in the yellow-green range (after white light), but as is seen in Figure 112, these hues require the longest time for complete adaptation. It can also be seen that red light reaches its maximum adaptation period in approximately ten minutes. Earlier studies by Haig (Ref. 152) as reported by Chapanis (Ref. 62) have indicated that dark adaptation for certain hues continue for several hours after the eyes are plunged into darkness. This study suggests that blue light requires the longest period of time for maximum adaptation.

As will be seen in the section on the point source of light, the different areas of the eye are differentially sensitive to light. This fact holds true for light adaptation also. The foveal area is most sensitive to the detection of light and is also most quick to reach total dark-adaptation. However, the immediate on-axis area of the fovea is less sensitive at lower illumination levels than the area immediately adjacent to the 4 degree foveal cone. Figure 113 indicates that although this area (2.5 to 10 degrees off the visual axis) requires a longer overall adaptation period, it is more sensitive to the detection light after the adaptation has been accomplished. This fact explains why dimly illuminated stars viewed directly at night may not be visible, but may be seen 'out of the corner of the eye'. This relationship, obviously, only holds for relatively low illumination levels.

In summary, the following general conclusions can be drawn:

1. The longer the duration of exposure to high pre-adapting luminance:
   a. the higher the instantaneous threshold
   b. the longer the re-adaptation period
   c. the slower the rate of re-adaptation
2. The higher the intensity of the pre-adaptation luminance:
   a. the higher the instantaneous threshold
   b. the larger the target must be to be instantly seen or resolved
   c. the longer the re-adaptation period
   d. the higher the target-background contrast required for rapid detection

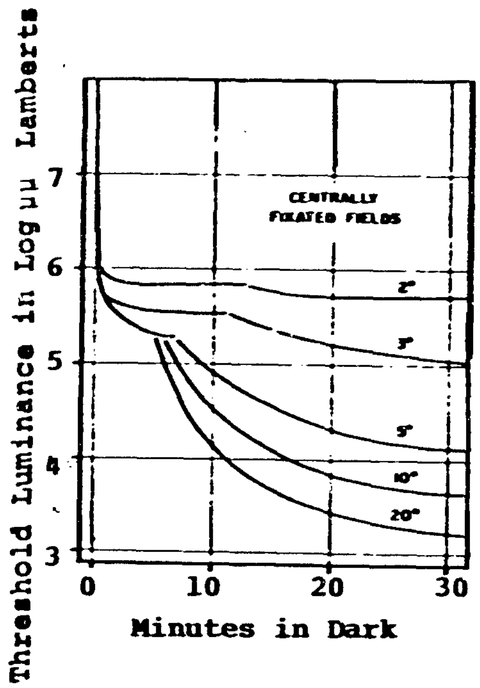


Figure 111. Dark Adaptation Curves for Centrally Fixated Areas of Different Sizes. (After Data from Hecht et al., Ref. 385)

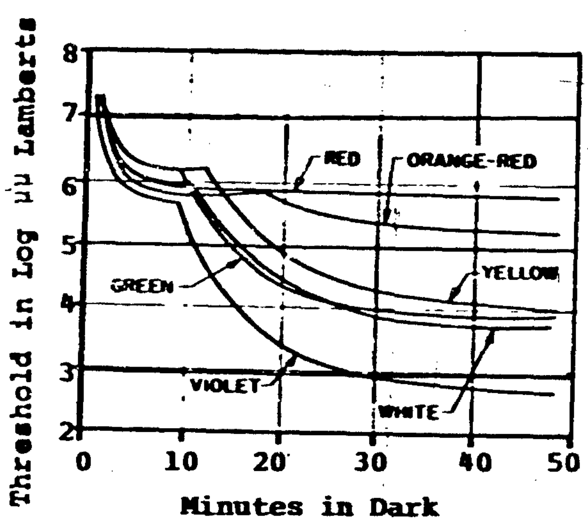


Figure 112. Luminance Threshold a Function of Wavelength of the Test Stimulus. (After Chapanis, Ref. 62)

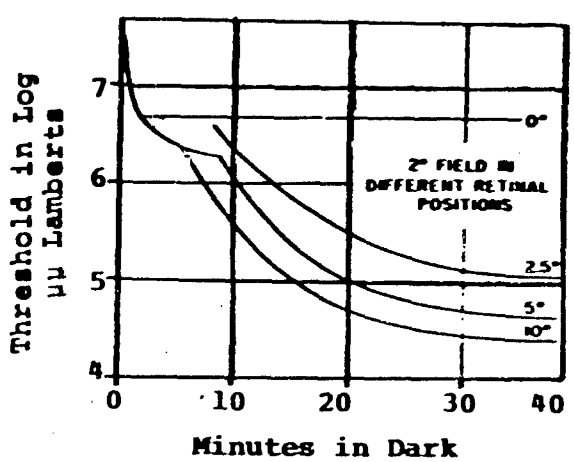


Figure 113. Threshold Luminance as a Function of the Region of the Retina Stimulated. (After Hecht et al., Ref. 385)

3. The larger the area of the visual target, the longer the adaptation period will be, a lower level of luminance will be required to be detected after adaptation.

4. Red hues will provide the quickest adaptation time, however, hues in the yellow-green range provide the best overall acuity factors.

5. The central foveal area requires a longer adaptation period, but provides the greatest overall acuity, except at very low luminance levels. At these low luminance levels, the area 2.5 to 10 degrees off the visual axis provides the quickest adaptation and the best acuity.

6. If the observer must do other visual tasks at higher luminance levels, acuity will not be seriously affected if the higher brightness is not more than 100 times as bright as the average brightness of the display screen.

EXPOSURE TIME AND VISUAL ACUITY

Increased luminance increases acuity linearly with exposure time when a target is displayed as a short flash (up to 0.1 second duration). This relationship is expressed by Block's law. On longer exposures (up to a few tenths of a second or longer), the time factor is less effective as expressed by Blondel and Rays' Law. Finally, above a critical time, the effect of light becomes independent of duration of exposure. These laws, which express the temporal summation ability of the visual system, may also be valid for moving objects as long as the moving image stimulates the same receptive fields of the retinal elements. Figures 114 and 115 are graphical presentations of the relationship of time (duration of exposure) and luminance level on acuity for stationary targets. It is observed that at any luminance level, less time is required to see larger objects. When size is held constant, less time is required to see higher luminance targets. When time is held constant, subjects were able to see smaller targets as the background luminance increased.

The range of luminance levels examined in this study were very small, and there do not appear to be any more complete studies of this functional relationship. Chapanis (Ref. 62) concludes that there is good reason to believe that time would become especially critical at luminance levels below cone vision. It is desirable to have data for this relationship over a larger range of lumination.

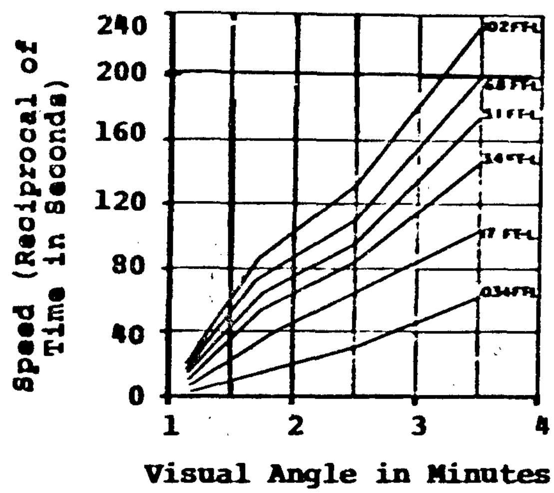


Figure 114. Acuity as a Function of Duration of Exposure of Viewed Object. (After Chapanis, Ref. 62)

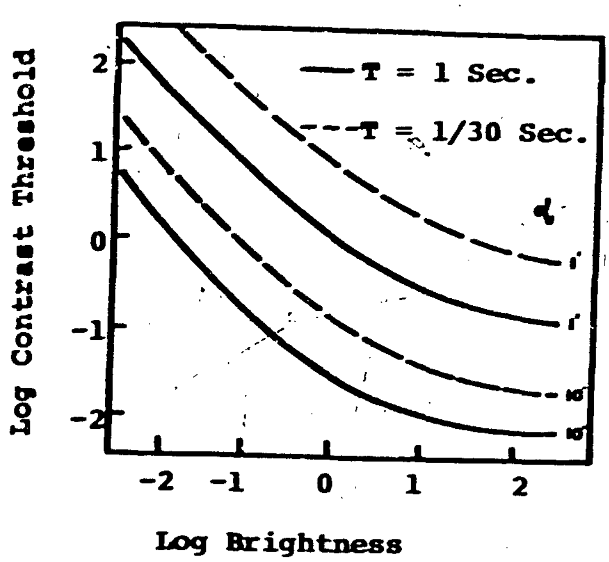


Figure 115. Contrast Thresholds as a Function of Target Size and Duration of Exposure. (After Schmidt, Ref. 290)

SPHERICAL ABERRATION

Examination of the surface of the cornea and the lens of the eye reveals that this surface is not perfectly spherical and that this shape is subject to change with changes in visual accommodation of the eye. This in part accounts for the fact that the optical density of the lens varies from one point of entry to the next and from moment to moment. Additionally, the transmittance quality of the total ocular medium varies as a function of the nature of the entering light, the adaptation level of the eye, and the aberration effects. Boettner and Wolter (Ref. 34) suggest that the maximum ocular transmittance is only about 81% and that this figure is restricted to the visible light range to which the eye is most sensitive (600 to 850 millimicrons). It can be seen, that light sources entering the eye under the above conditions are subject to refraction; the degree of refraction depends upon the angle of incidence of the light relative to the eye, the point of entry into the eye, and the wavelength of the entering light source.

Fincham (Ref. 119) states that spherical aberration is greatest on the periphery of the cornea and of the lens. Pupillary constriction, consequently, improves the quality of the image formed on the retina by excluding light that passes through the peripheral portions of the cornea and the lens (this refracted light 'scatters' within the ocular medium and thus reduces acuity by "blurring" the image edge). Pupillary constriction is induced by increasing the brightness level of the image being viewed. Conversely, low luminance levels dilate the pupils and thus greatly increase the aberration effects. Bryam (Ref. 52) concludes that if the pupil diameter is maintained between 2.5 and 4 mm, the effects of spherical aberration will be negligible in comparison to other diffractions. If, however, the diameter is allowed to increase above this value (precise value varies with the individual), it may have a significant effect on low-light level (and night viewing) acuity, producing blurring of the retinal image in worst cases.

The relative luminance efficiency of light entering the eye on the periphery has been questioned. Graham (Ref. 145) conducted a controlled experiment which demonstrated that all the rays (beams of light) entering the eye reach the retinal surface with nearly equal intensity. In an effort to explain the Stiles-Crawford effect (which states that a marginal ray is usually less effective as a stimulus for vision than a ray that reaches the same point on the retina but which passed through the center of the pupil), he concluded that the disproportionately low efficiency of the marginal rays was a consequence of their direction of incidence to the receptors (Figure 116).

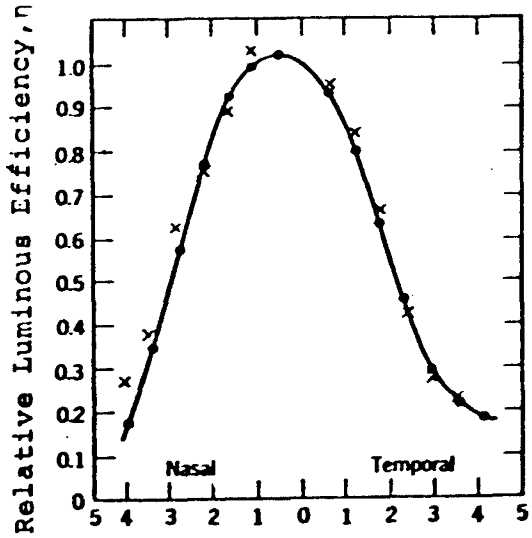


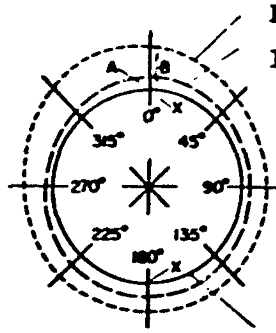
Figure 116. Relative Luminous Efficiency of Light Entering the Pupil in Horizontal Plane Through the Center of the Eye. (After Stiles and Crawford, Ref. 326)

It appears that the rods do not manifest the Stiles-Crawford effect as significantly as do the cones. This indicates that retinal illumination as such, cannot be taken as an appropriate indication of the effectiveness of visual stimulation. A true measure must specify pupil size and luminance level for the given situation. Only when the latter has been accomplished can one speak of the product in terms of trolands (uncorrected for the Stiles-Carwford effect).

Another phenomenon in part induced by aberration of light is the "irradiation effect" that takes place on the retina. An observer attempting to measure the boundaries between light and dark areas on a visual display will perceive the boundaries to lie towards the darker areas. This irradiation effect is operationally defined as the spreading of a bright image on the retina of the eye making the diameter of a bright object appear to be larger than it really is (Ref. 20). The magnitude of the effect of irradiation varies with the luminance of the bright object, the contrast of the object against the background, the optical system used (if any), the dark adaptation of the observer, and the individual himself. The irradiation phenomenon results in a distortion of the apparent shape of the observed object; the distortion increases as a function of the luminance level. When, however, the object luminance increases above a critical point, the effect is termed "glare" (see Figure 117 for the effects of glare source luminance upon perceived size and

CIRCLE

Full Intensity Edge = 4,230 Ft. L.
Intermediate Intensity Edge



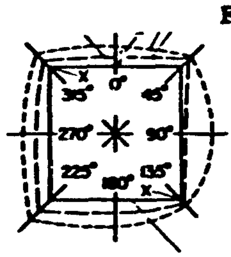
MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	6'32.3"	20'35.9"
45°	7'46.1"	13'16.5"
90°	9'38.3"	12'39.2"
135°	6'9.1"	12'47.0"
180°	14'55.0"	13'8.0"
225°	5'4.9"	12'26.6"
270°	3'8.0"	13'8.0"
315°	2'26.2"	20'33.0"
MEAN	6'31.1"	14'29.5"

Zero Intensity Edge

X-X Distance = 1 33'13.3"

SQUARE

Full Intensity Edge = 4,230 Ft. L.



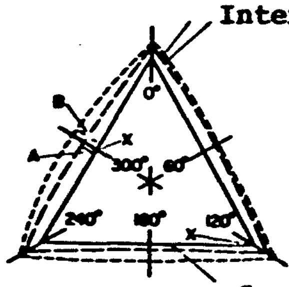
MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	5'16.3"	8'59.2"
45°	7'1.8"	7'57.4"
90°	0'37.9"	12'3.3"
135°	5'54.5"	8'30.0"
180°	4'37.6"	11'7.8"
225°	8'34.4"	14'9.2"
270°	3'59.7"	9'22.4"
315°	9'49.1"	14'18.5"
MEAN	5'36.6"	10'34.2"

Zero Intensity Boundary

X-X Distance = 1 24'59"

TRIANGLE

Full Intensity Edge = 4,230 Ft. L.
Intermediate Edge



MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	6'41.4"	6'58.3"
60°	6'2.6"	8'0.8"
120°	6'35.4"	10'8.7"
180°	3'7.7"	7'15.7"
240°	9'37.2"	11'3.1"
300°	6'44.2"	13'34.8"
MEAN	5'34.0"	9'22.2"

Zero Intensity Boundary

X-X Distance = 1 30'50.7"

Figure 117. Effects of Glare-Source Luminance Upon Perceived Size and Shape of Circles, Squares, and Triangles. (After Haines, Ref. 153)

shape of objects), and consequently the object has a propensity to appear round, regardless of original shape.

Under night or low-light level viewing conditions this spreading effect is accentuated when the eye of the observer is not adapted to the brightness of the light portion of a visual display (Ref. 23). The effect is particularly pronounced for individuals with eyes adapted to a dark surround. Because of the spreading of the light portion of the display over the darker portion under low-light viewing conditions, McCormick (Ref. 230) recommends that for low light level or night viewing condition, light alphanumerics should have thinner stroke widths and darker alphanumerics should have thicker stroke widths than those used in normal daylight viewing.

Perception of a moving point source in close proximity to a source of high luminance will influence the correspondence between the actual physical form of the object and the perceived shape of the object. Haines (Ref. 153) recently investigated this phenomenon. Five highly trained subjects viewed stimulus configurations through an artificial pupil which provided a 19.5 degrees field of view. A moving "star" (1" diamet was used as a test spot to determine the characteristics of the edge distortion effect produced by the glare source of 4250 Ft. Lamberts. It was found that the distance, in visual angle, from the perceived edge of a glare source at which the star disappeared (or reappeared) is directly related to the luminance of the glare source. This appears to be a survilinear function which accelerates rapidly at about 1,000 Ft. Lamberts and begins to decelerate at about 4,000 Ft. Lamberts as illustrated in Figure 118.

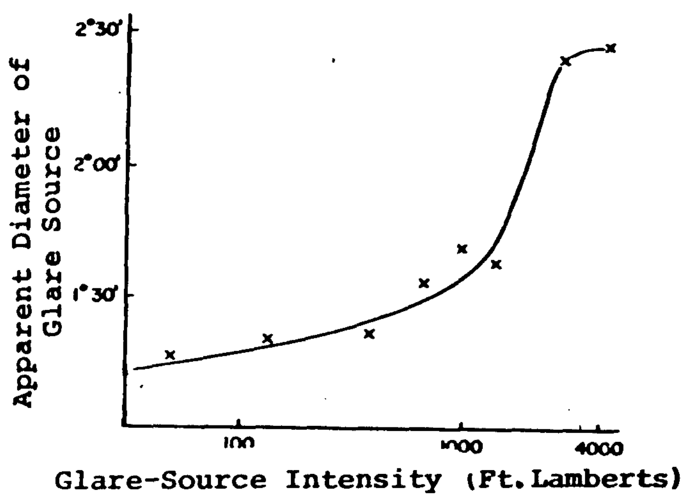


Figure 118. Effects of Glare Source Intensity on Apparent Size. (After Haines, Ref. 153)

The above findings are somewhat greater than those obtained for a two point source by Ogle (Ref. 258). He found that the star disappeared and reappeared at different apparent distances from the edge of the glare source, depending upon the type of geometry found in the glare source. The star was found to disappear and reappear at a greater distance from the edge of a curved surface than it did from the edge of a straight surface under similar circumstances.

It appears that two primary conclusions can be drawn from the effect of irradiation for the design of airborne displays:

a. Critical visual tasks should be confined to a vision envelope that excludes extremely bright sources of light aimed at the observer's eyes.

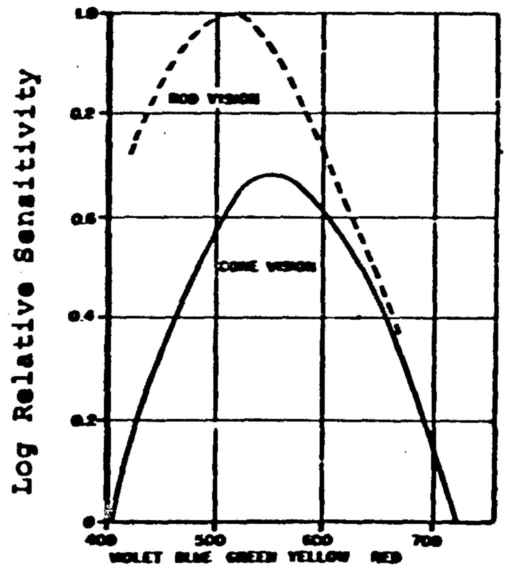
b. Visual identification of bright sources on the basis of size or shape alone may lead to identification errors, at least for some shapes.

The above data were derived for the most part from studies conducted at relatively low luminance levels. There is a need for more examination of this problem under actual operational luminance levels (10,000 + Ft. Candles) before a full range of valid generalizations can be made.

CHROMATIC ABERRATION

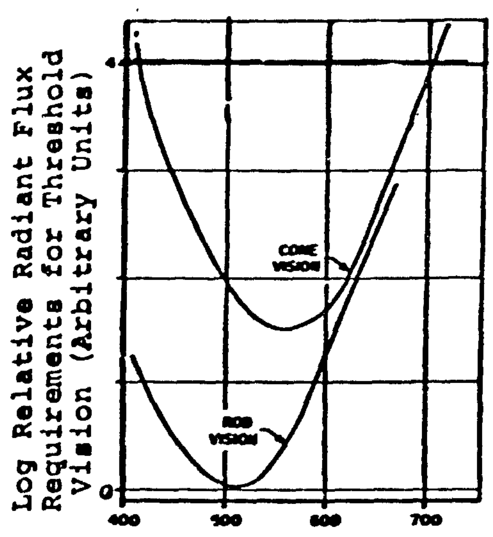
The visual effect produced by a light stimulus impinging upon the eye depends also upon the relative energies of the wavelengths of light incident on the retina of the eye (Figure 119). The visual system, for example, identifies definite mixtures of various wavelengths as 'white' light. Likewise, because of the energy composition of 'white' light, this light is the most conducive to discrimination by the eye. That is, the eye can detect a smaller point source of light if the luminance emitted is white. The resolving power in the area of yellow-green wavelengths is almost equal to that of white light. For red, however, the resolving power of the eye is only about one-third as good as for white light and for blue it is only about one-fifth as good as white.

Myers (Ref. 253) suggests that the lens of the eye functions, in some respects, similar to a prism in that both refract light. In both the eye and the prism, the shorter wavelengths are refracted (bent) to a greater extent than the longer wavelengths. Duke-Elder (Ref. 108) states that the degree of refraction is related in inverse proportion to the wavelength of the light entering the eye. Myers (Ref. 253) states that only



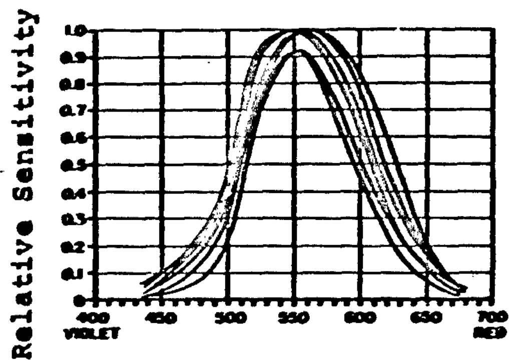
Wavelength in Millimicrons

a. Relative Sensitivity to Radiant Flux as a Function of Wavelength. (After Hecht and Williams, Ref. 62)



Wavelength in Millimicrons

b. Relative Amount of Radiant Flux necessary to Stimulate Rods and cones. (After Chapanis, Ref. 62)



Wavelength in Millimicrons

c. Individual Luminosity Curves (After Data from Gibson and Tyndall, Ref. 139)

Figure 119. Relative Sensitivity of the Human Eye to Different Hue Wavelengths.

one wavelength can be focused on the retina at a time. When viewing a white light object brought to focus, the eye adjusts itself (accommodates) to the yellow portion of the spectrum present in the white light. Consequently, the blue and red regions of the spectrum will both be equally unclear, with their focal points falling in front and to the rear of the focal plane, respectively. The larger the diameter of the pupil of the eye at the time of entry of the light (the lower the display luminance level), the more 'out-of-focus' the blue and red light sources will appear.

Mitchell and Mitchell (Ref. 242) have referred to this aberration as "chromatic myopia" and found that under blue light, distant objects (6 feet or more away) are images in front of the retina and the normal emmetropic eye (normal accommodation range) is not able to adjust to clearly focus them. In their study, they found that the accommodative power of the eye is already at its minimum when viewing distant objects and to compensate for the aberration of blue light, corrective lens were used for which the appropriate dioptic values (reciprocal of the focal length of the lens) were determined. These corrective lenses had the effect of adjusting the focal point of the stimulus image under blue light so that it fell on the retina of the eye. Under these conditions, observer performance with blue light was indistinguishable from performance under white light conditions without corrective lens. Performance under red light, however, could be expected to deteriorate proportionately.

Jones (Ref. 186) states that the myoptic reaction of the eye to blue light (focusing in front of the retinal plane) is of critical concern because of its effect on visual acuity. She suggests that the use of small colored stimuli (or larger stimuli viewed at a great distance) is inadvisable for presentation of critical information. Conover and Kraft (Ref. 87) suggest that any stimuli subtending a visual angle of less than 20 minutes on an information display should not be color coded. Myers (Ref. 253), however, suggests that the "critical" size to which color may be applied in a visual display varies with the particular situation and with the color employed. Myers judged that, with the exception of blue, the small differences in acuity resulting from accommodation differences with various colors would not be a serious impediment to the use of color in visual displays. Blue, however, should be excluded, since the eye does focus this myoptically, and even though larger symbol sizes may result in correct identification, the image will remain out of focus and consequently will not appear "sharp". Additionally, he states that blue is a "subjectively non-desirous" color for most visual displays.

ACCOMMODATION OF THE EYE

Mention has already been made that accommodation is the focusing of the eye from one fixation point to another fixation point. A number of factors interact to influence the accommodative process, too many in fact to completely cover here. The primary factors as far as display designers are concerned, however, are the intensity level of the emitted luminance, the spectral composition of the emitted hue and the age of the observer.

In opathalmology it is customary to use the diopter as the unit of measurement in describing the refractive power of the lens. The diopter is defined as the reciprocal of the principle focal length or the conjugate focal length expressed in meters. A normal youthful eye, for example, varies from about 63 diopters in near vision (Ref. 226). Although a number of curved surfaces and transparent media constitute the geometric optical system of the eye, the entire mechanism of accommodation rests in the elastic lens of the eye. In particular, it is the change in curvature of the anterior lens surface which determines the effectiveness of focus.

In display design, consideration should be given to the age span of the using population; for age is a primary consideration in the accommodative process. Regardless of the condition of distant vision, a progressive loss of accommodation takes place with age. Figure 120 indicates the average loss of accommodation experienced by about 4,000 individuals. Luxemberg and Kuehn (Ref. 226) state that this loss of accommodation capability is the result of weakening of the ciliary muscles and, most importantly, the progressive inelasticity of the lens itself until muscular exertion is of little avail. In light of the above discussion on chromatic aberration, the selection of the hue to be emitted from a display should take into account the progressive loss of this power. Colors near the ends of the visual spectrum (particularly red and blue) should not be used in applications where the display is to be viewed by individuals with short dioptic ranges (age 45 and up, depending upon the individual; Southall, Ref. 320). Likewise, careful consideration should be given to the use of two or more colors on the same display, if it is to be viewed by this same age group. These values are rough guides and not absolute. More research is required in this area to establish a set of 'absolute values' for display design.

DYNAMIC VISUAL ACUITY

Dynamic visual acuity refers to the recognition of detail when the observer, the test object, or both are moving (in comparison to static acuity where both observer and test object

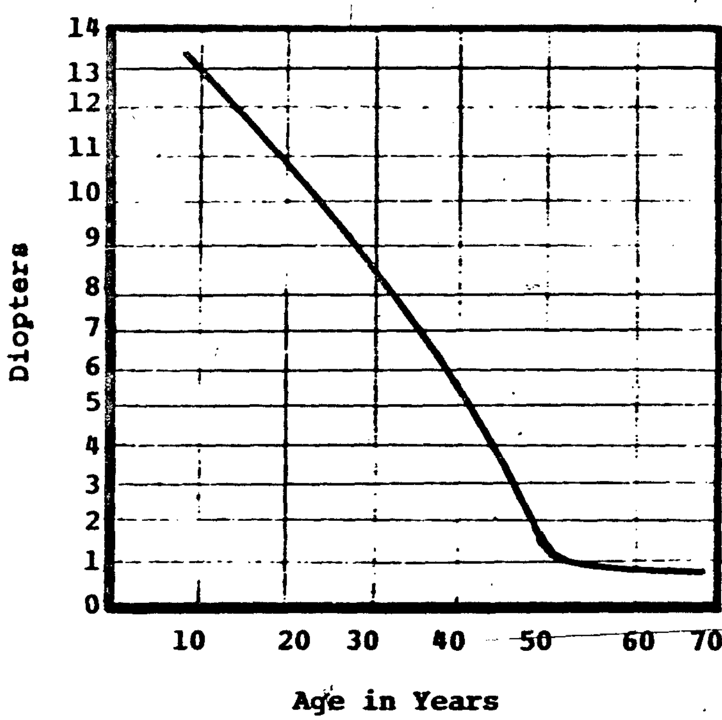


Figure 120. Amplitude of Accommodation as a Function of Age. (Based on 4,000 Measurements. After data from Southall, Ref. 320)

are both stationary). Dynamic acuity shows a predictable impairment with increasing angular velocity, with noticeable deterioration beginning with an angular velocity of about 20 degrees per second. Generally, peripheral vision is more affected than central vision, especially at higher velocities, but the degradation in acuity is about the same for moving observer or moving target. Higher dynamic acuity is possible if the head is allowed to move freely than if the head is restrained. Both acuities increase with increasing illumination (up to 1000 Ft. Lamberts) and exposure time (up to 16 seconds exposure time). Dynamic acuity is subject to more rapid deterioration with anoxemia, reduced illumination levels, visual fatigue and with advancing age. Vertical movement produces greater deterioration than horizontal movement, and the effect of vibration is about equal on both vertical and horizontal movement. Certain individuals are 'velocity resistent' (subject to minimal acuity loss with increasing angular velocity; Ludvigh, Ref. 222) while other individuals are 'velocity susceptible' and suffer severe acuity degradation with slight angular velocity).

Ludvigh and Miller (Ref. 223) conducted a study to examine the effects of increased angular velocity on visual acuity and to determine, what, if any, relationship exists between static and dynamic acuity. Eighteen visually screened subjects viewed thirteen Landolt Rings, the critical detail gaps of which varied from 0.75 to 11.25 minutes of arc. The illumination on the test objects was approximately 25 Ft. Candles, and the test objects were viewed at a distance of four meters (approximately 156 inches). Angular velocity was obtained by rotation of a viewing mirror and ranged from 10 to 170 degrees per second. The observer's task was to correctly locate the gap in the ring as it crossed the display area. For purposes of analysis, the subjects were divided into three groups based on their pre-test performance. Group I (five subjects) consisted of subjects tested up to angular velocity of 110 degrees per second, Group II (eight subjects) consisted of subjects tested up to 140 degrees per second, and Group III (six subjects) were tested up to 170 degrees per second.

The results of the study are summarized in Figure 121. The circles, crosses and triangles represent experimentally determined points while the solid lines are graphs of the equation:

$$Y = a + bx^3$$

where: Y = visual acuity in min of arc

x = angular velocity in degrees per second, and

a = curve fitting constant (value not specified)

b = curve fitting constant (value not specified)

This study illustrated that the relationship, if any, between static and dynamic acuity is extremely little. Ludvigh and Miller also found that individuals possessing similar static acuity differed markedly in dynamic acuity. Figure 122 illustrates the difference in dynamic acuity between two subjects, both of whom were known to have 20/20 static acuity.

Miller (Ref. 238) conducted a similar experiment to the one reported by Ludvigh and Miller in which he tried to determine if horizontal movement produced the same rate of degradation of acuity as did vertical movement. Nine male subjects were tested using angular velocities of 20, 80, 110, and 140 degrees per second in both the vertical and horizontal axis. Intensity of illumination, exposure time and other variables were held constant.

The results of this phase of the experiment are summarized in Figure 123. It can be seen from Figure 123 that a consistent and statistically significant difference exists between vertical and horizontal movement. Vertical movement produced a consistently greater degradation of acuity.

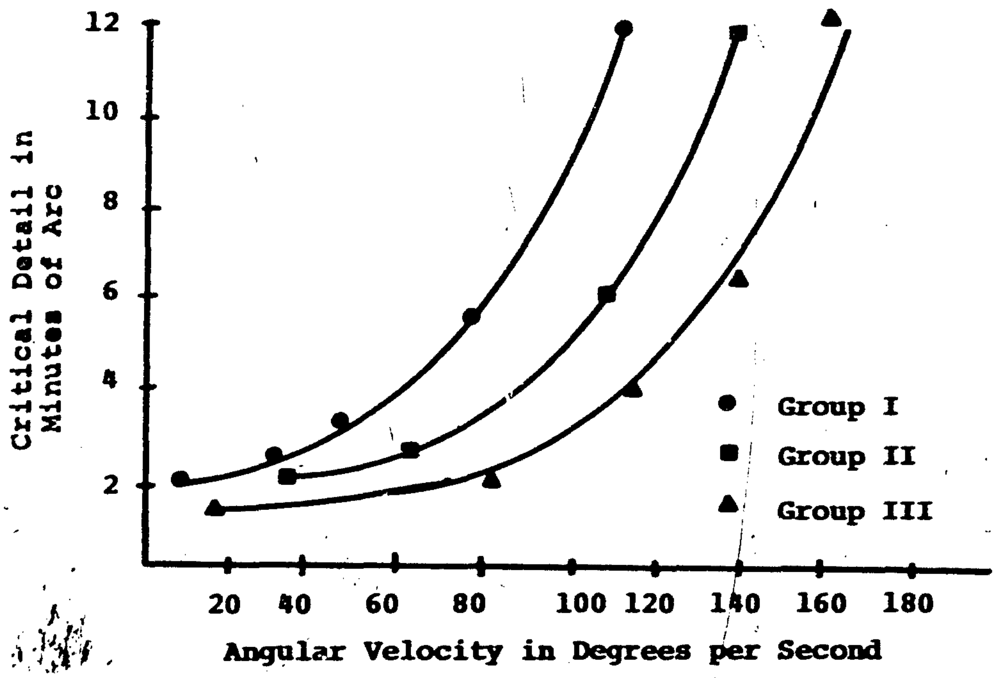


Figure 121. Threshold Values for all Subjects Grouped According to Pre-Test Performance Levels. (After Ludvigh and Miller, Ref. 223)

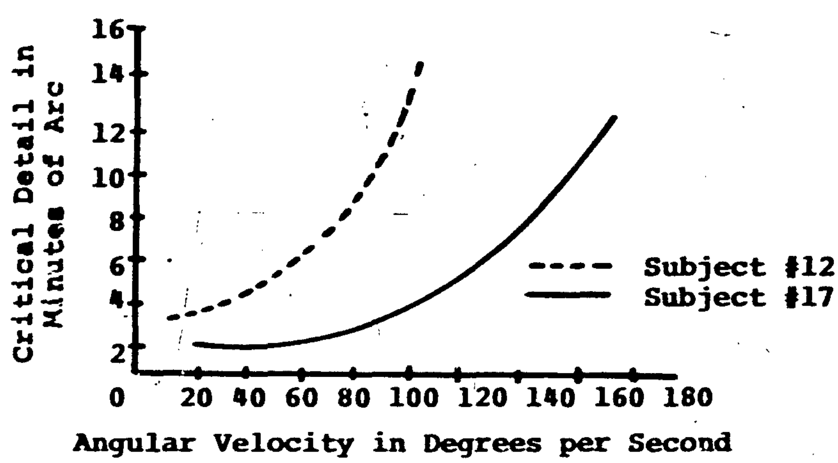


Figure 122. Difference Between Two Subjects in Degradation of Dynamic Acuity with Increasing Angular Velocity. (From Ludvigh and Miller, Ref. 223)

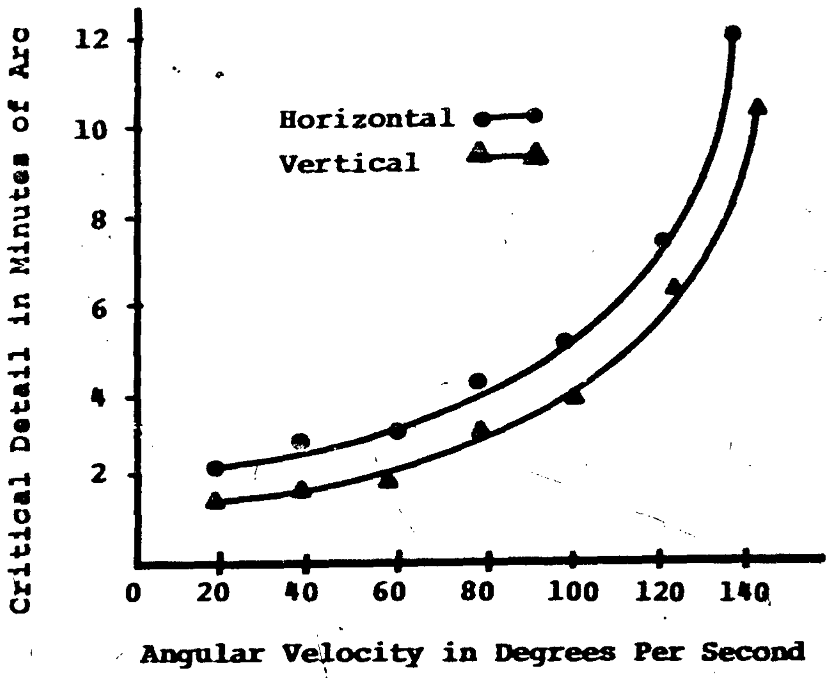
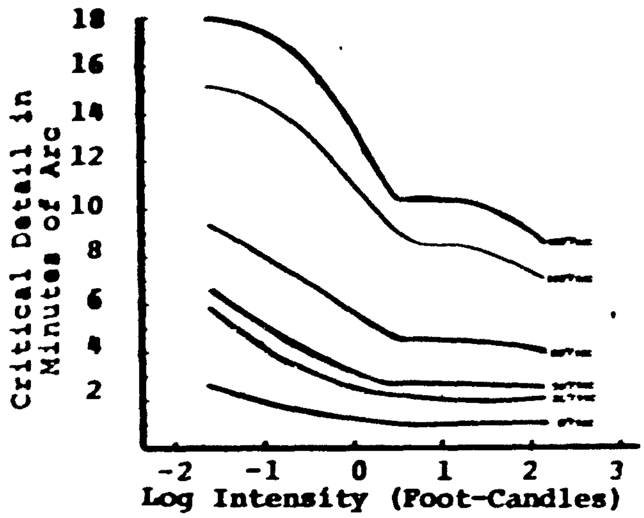


Figure 123. Visual Acuity as a Function of Horizontal Vs. Vertical Movement. (After Data from Miller, Ref. 238)

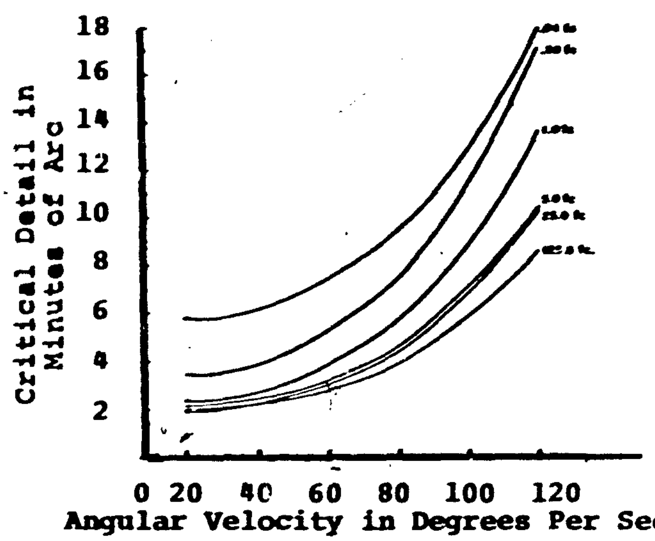
Ludvigh (Ref. 221) found that when the test [illegible] is moving, high intensities of illumination may be advantageously employed to increase visual acuity. In his study, Ludvigh found that with angular velocity of 90 degrees per second, acuity was still improving at an intensity level of 505 Ft. Candles. He advises that illumination as high as 1000 Ft. Candles may be beneficial when viewing rapidly moving objects.

Miller (Ref. 238) conducted another study to examine if the above effects holds true if the observer, instead of the test object, is rotated. He had six observers view a target with angular velocity ranging from 0 to 120 degrees per second (subjects rotating) under illumination levels ranging from 0.004 to 125.0 Ft. Candles. The test object was viewed monocularly for 0.5 second.

The results of this study indicated that dynamic acuity improved at all velocity levels as the illumination level increased (see Figure 124a). By the time the intensity has reached 10 Ft. Candles, the curve represents the threshold determined under static conditions and at angular velocity of 20 degrees per second are practically asymptotic and little



a. The Effect of Increased Test Chart Illumination on Visual Acuity at Each of the Six Angular Velocities of the Test Object.



b. Effects of Increased Angular Velocity on Acuity at Six Different Angular Velocities.

Figure 124. Acuity as a Function of a) Illumination Level and b) Angular Velocity. (After Miller, Ref. 238)

further increase in acuity is achieved with increased illumination. At higher angular velocities, however, acuity increased significantly as the illumination level is increased all the way up to 125 Ft. Candles.

Figure 124b plots acuity as a function of angular velocity for the different illumination levels examined. It can be seen from this figure that dynamic visual acuity deteriorated with increased angular velocity at each of the six illumination levels employed. The rate of deterioration, however, was greater at lower luminance intensities than at higher intensities.

These studies by Ludvigh and Miller indicate that dynamic visual acuity is a function of the luminance level of the display and that increasing the luminance level improves dynamic acuity. Unfortunately, the studies were conducted with achromatic stimuli over a limited range of illumination. It would be valuable to know the precise effects of luminances in the 5 to 10,000 Ft. Lamberts range on dynamic acuity, especially in view of the fact that this is the normal daylight viewing range of illumination and that airborne acuity, for all practical purposes, is limited to dynamic acuity.

The perception of movement itself is affected by a number of factors. Graham (Ref. 143) ascertained that the velocity threshold (minimum rate of movement required for the perception of motion) is about 1 minute of arc per second and that displacement threshold (minimum distance an object must move for movement to be detected) is about 20 seconds of arc under 'ideal' illumination conditions. Leibowitz and Lomont (Ref. 213) conducted a study to determine the effects of illumination levels and exposure times upon the isochronal threshold velocity (minumum rate of target displacment necessary for the detection of movement at a constant duration of exposure). White rectangular squares each subtending 15 minutes of arc were viewed at 90.6 inches by three subjects seated in a dark room. Display luminance levels of 0.016, 0.05, 0.16, 0.5, 5, 50, and 500 millilamberts and exposure times of 0.12, 025, 1, 2, and 16 seconds were used. The white rectangles were mounted on a moving belt which had velocities ranging between 0.1 minutes of arc and 76 minutes of arc per second. The single subject was instructed to report when movement was apparent.

Results of the study indicated that threshold velocity decreased with increasing illumination levels (Figure 125), rapidly at first and then more slowly until it reached a limit after which increased illumination had no effect on performance. Increasing the exposure time shifted the entire function to lower values (Figure 126). These findings are compared with the findings of Rock (Ref. 280) who found that as luminance was varied from 0,005 to 10 Ft. Lamberts, the velocity threshold decreased from 0.40 to 0.17 minutes of arc per second.

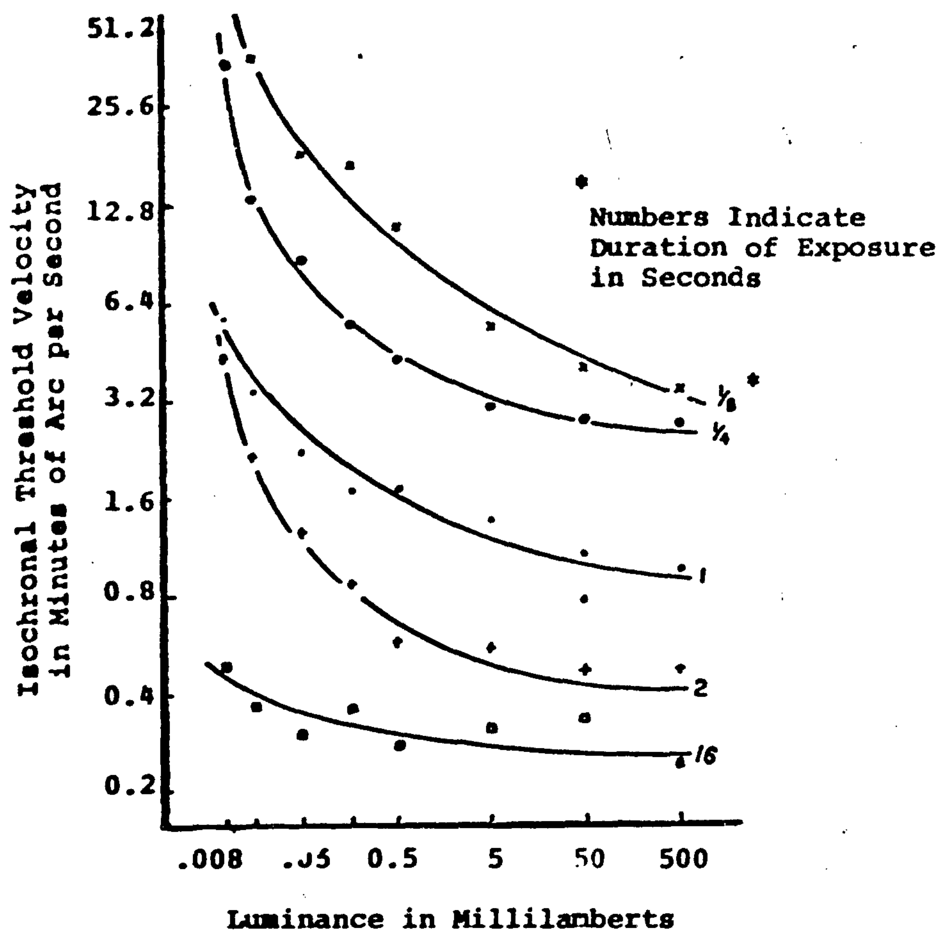


Figure 125. Isochronal Threshold Velocity as a Function of Luminance Level and Duration of Exposure. (After Leibowitz and Lomont, Ref. 213)

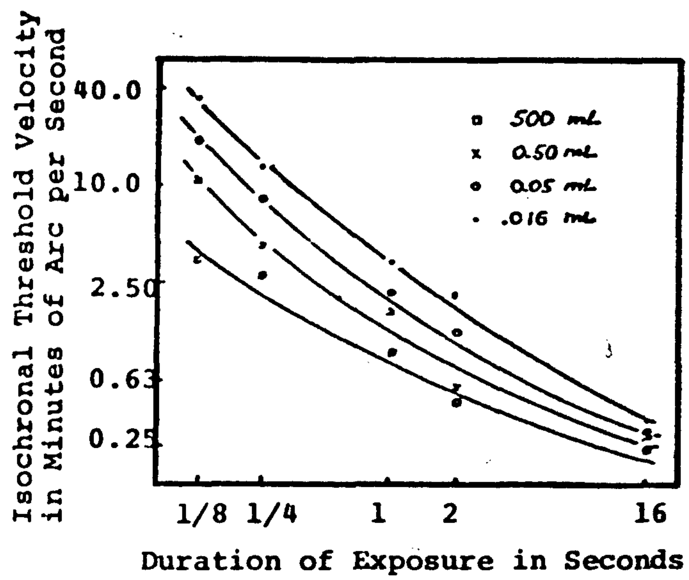


Figure 126. Isochronal Threshold Velocity as a Function of Duration of Exposure with Target Luminance as a Parameter. (After Leibowitz and Lomont, Ref. 213)

The luminance levels used in the above studies were quite low, but the results tend to indicate a trend of decreased threshold with increasing illumination. At present, it is not feasible to generalize to the high luminous output displays currently employed nor to predict the effects of environmental factors (stress, acceleration, vibration, high ambient illumination) on the detection of motion.

RETINAL IMAGE LOCATION

At luminance levels of about 0.001 Ft. Lamberts, all parts of the visual field are equisensitive (Ref. 328). At this luminance, the acuity of the peripheral portions of the eye is the same as the acuity of the foveal portion. However, as the intensity of the emitted luminance is increased, a marked increase in foveal acuity is noted while the peripheral areas show a slight increase and then tend to level off (Figure 127). As discussed in the section on Luminance Level, foveal acuity continues to increase, as a function of luminance increases, over a considerable range (with other factors held constant).

At a fixed level of background luminance (daylight viewing conditions), the relative photic acuity varies as a function of the angular viewing position relative to the visual axis. It is observed that visual acuity deteriorates rapidly as the object viewed is moved towards the periphery of the eye. Chapanis (Ref. 62) states that with viewing angles of only four or five

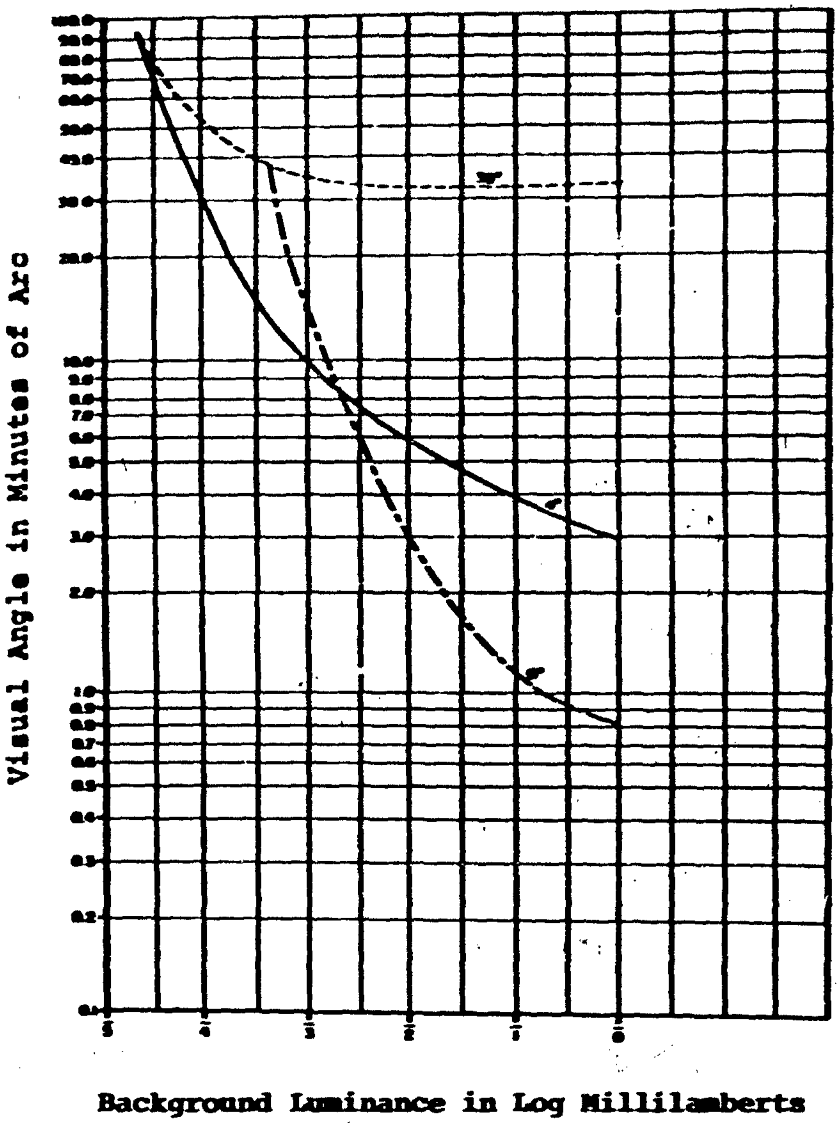


Figure 127. Visual Acuity at Different Viewing Angles Away from the Visual Axis as a Function of Background Luminance. (After Wulfeck et al., Ref. 363)

degrees off the visual axis, visual acuity is reduced by 50% for a given luminance level. Luxemberg and Kuehn (Ref. 226) state that at visual angles of only one degree off the central axis, acuity is only 67% as good as direct on-axis viewing. At angles of 40 to 50 degrees off the visual axis, acuity is reduced to 4% that of direct foveal vision.

It can be concluded from Figure 128 that beyond a foveal cone of 10 degrees (5 degrees in any direction away from the visual axis), visual acuity falls off to such an extent that it is impractical for information display. It is therefore necessary for the display designer to so arrange the display situation that the critical information is directly addressed by the observer with a minimum of head movement. Extreme head movement away from normal straight-ahead position involves a loss of acuity, even though the visual target is viewed directly along the visual axis.

It is to be noted that the above values were derived under laboratory condition with optimized figure-ground contrast using a white light source. Additionally, no vibration or other environmental degrading factor (changing illumination, filters or faceplates, visual fatigue, or stress) were present. Rubinstein and Kaplan (Ref. 386) have shown that vibration can reduce foveal visual acuity, in a worst-case, by as much as fifty percent. Considering the effects of vibration, the maximum effective visual cone of 10 degrees is reduced to 5 degrees (2.5 degrees off the visual axis) in the presence of moderate to severe vibration.

Other environmental factors are known to affect foveal visual acuity. A study conducted by Paige and Kama (Ref. 389) indicates that short-term exposure to weightlessness aboard an aircraft has a detrimental effect on visual acuity during the period of the exposure. Thirty-six subjects were flown in the mid-section of a C-131 aircraft to produce the transient weightless condition, and during the period of weightlessness were to view a standard Busch and Lomb "Armed Forces Vision Tester" installed in the aircraft. The subjects were tested for acuity prior to take-off and then during the flight. The results indicate a general increase in the required visual angle for the detection of the test targets by the subjects as the testing environment changes from laboratory conditions to a zero G condition. The zero G score average indicated an approximate 6% increase in required visual angle to identify the target at threshold acuity.

In another experiment, Paige and Kama (Ref. 388) examined visual acuity in relation to body orientation. Twenty-four subjects were tested on the "Armed Forces Vision Tester" in the upright, inverted, prone and supine positions. The results reveal a general decrement in acuity from the upright to the

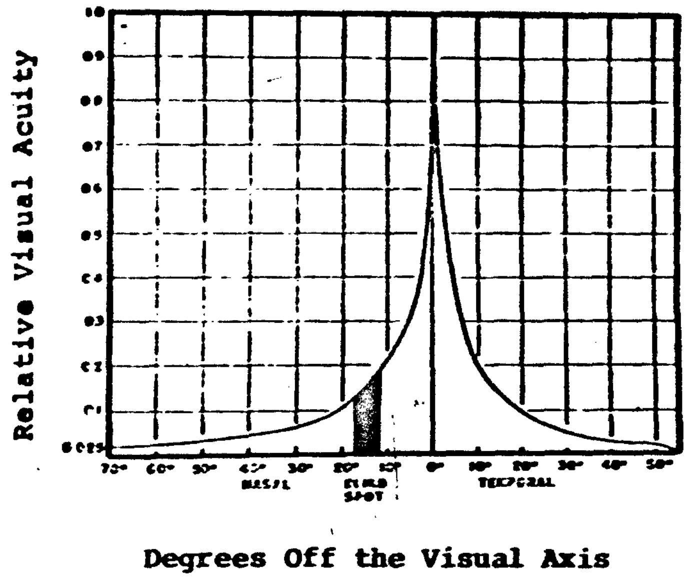


Figure 128. Relative Visual Acuity at Different Angles from the Fovea for Photopic Vision. (Adapted from Wulfeck et al., Ref. 363)

prone, supine and inverted position (Table 58). The data show a distinct difference between the near and far score, with the latter showing smaller visual angles generally, but indicating that far acuity suffers somewhat greater loss with changes in viewing conditions than does near acuity. The threshold visual angle for far vision increased 19% as compared with approximately 13% for near vision when going from the upright to the inverted position.

An average decrement of about 5% is found when body orientation changes from upright to prone position. An additional 5% decrment occurs from the prone to the supine position with the head inverted and another 5% loss from the supine to the inverted position. This loss is comparable to the loss of acuity at 3-G (Ref. 349).

Maximum visual acuity is achieved only under direct on-axis viewing in the upright viewing position under appropriate lighting conditions. A number of environmental factors degrade this performance and consequently allowances for their presence must be made. These factors include vibration (discussed in section addressing Vibration), bodily orientation, viewing angle, stress and visual fatigue, altitude and G-force. Unfortunately, few data exist from studies conducted under operational conditions that included these factors. Hence, it is necessary to estimate the true total amount of degradation of visual performance in the presence of degrading factors.

Table 58. Visual Acuity Degradation as a Function of Body Orientation. (From Paige and Kama, Ref. 388)

Body Position	Visual Acuity Decrement
Upright	0%
Prone	5% (Approximate) Average for near and far vision
Supine	5% (Approximate) Average of near and far vision
Inverted	5% (Approximate) Average of near and far vision
Total Decrement Near-Vision	13% (Approximate) Inverted Position
Far-Vision	19% (Approximate) Inverted Position

POINT SOURCE OF LIGHT

There appears to be some confusion in the literature as to the size of the light source which can be considered a point source to the human eye. A psychophysical definition of a point source is given by Ricco's Law which states that the produce of the threshold contrast and the solid angle subtended by the stimulus are constant for any given adaptation level. Guyton (Ref. 151) states that theoretically a point of light from a distant source of light, when focused on the retina, should be infinitely small. However, since the lens system of the eye is not absolutely perfect, such retinal spots ordinarily have a diameter of about 11 microns (even under maximum visual acuity conditions). It is pointed out that the average diameter of the cones in the eye is approximately 2 to 3 microns, which is one fourth the size of the light spot. Nonetheless, he concludes that since the point source of light has a bright center and shaded edges, a person can distinguish two separate points if their centers lie approximately 2 microns apart on the retina, which is slightly less than the width of a retinal cone. Hence, the acuity of the perfect eye is limited at least to some extent by the size of the retinal cones themselves. He concludes that the maximum visual acuity of the human eye for point sources of light (conditions not specified) is 26 seconds of arc.

The size of the retinal image of a point source of light is influenced in part by the diameter of the pupil of the eye upon entry of the light source. Smaller pupil diameters tend to

'concentrate' the light and consequently produce smaller retinal images. Data from several studies on this subject were collected by Voss (Ref. 337) and are presented in Figure 129. It is evident that the data he obtained lacked reliability and consequently he suggests that for safety, the dotted line he inserted should be used as the minimum size of the retinal image point. It is noted that pupil diameters below 2 mm rarely occur (except under extremely high illumination conditions). With pupil diameters above 6 mm, the increase in incident light does not produce increases in retinal light concentration since the light from the borders of the pupil are so badly focused.

Figure 130 shows the minimum visual angle for a point source at different background luminances. It is noted in this figure that the visual angle increase as the background luminance decreases. The contrast ratio for this figure was not specified.

Figure 131 demonstrates that increasing the size of the light source will increase its effective brightness and visibility. Wulfeck et al. (Ref. 363) state that if the lumens emitted per unit area are held constant, the target with the larger area will obviously emit a greater total number of lumens and thus deposit a greater number on the eye of the observer. Conversely, by increasing the lumen emission per unit of area, a smaller area will appear as bright (or be detected as readily) as a larger area with less luminous output. Likewise, with increased lumen emission per unit area, a smaller area (visual angle will be required for detection.

Ogle (Ref. 258) measured the minimum angle of resolution of two small self-luminous objects viewed against a non-luminous background. His findings indicate that the minimum angle required for the discrimination of the two points tends to increase as a function of the luminance level of the objects. If the two points sources were viewed against different background illuminations, the minimum angle required for separation was found to depend entirely upon the contrast of point source and background and not upon the absolute value of the background luminance. He found that the minimum angle of resolution increased linearly as a function of the logarithm of the luminance ratio (I_s/I_b) (I_s = luminance intensity of the point source and I_b = the intensity of the background) from a luminance ratio of approximately 100 to approximately 5×10^4. The highest luminance ratio in this study required a minimum angle of 4.0 minutes of arc for a glare-source luminance of 4.00 millilamberts with a background luminance of 0.07 millilamberts.

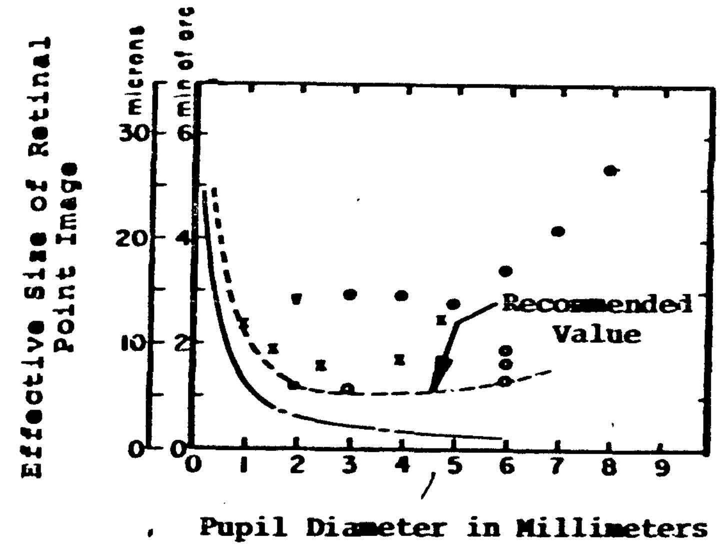


Figure 129. Minimum Size of Retinal Image of a Point Source as Derived from Several Investigations. (After Vos, Ref. 337)

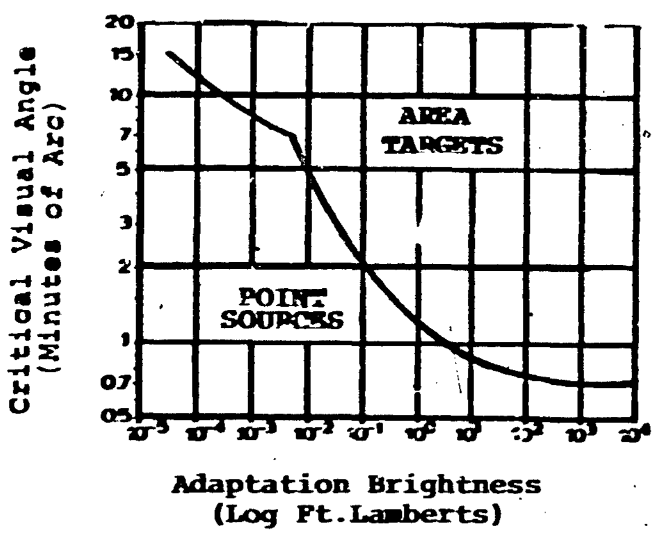


Figure 130. Critical Visual Angle for Point Source of Light Vs. Critical Angles for Area Targets. (After Seyb, Ref. 299)

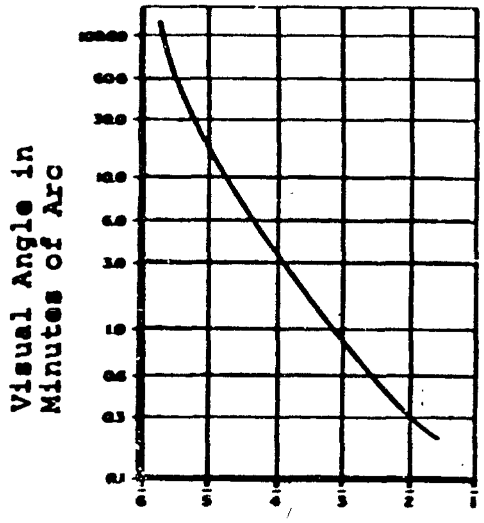


Figure 131. Minimum Visual Angle a Light Source can Subtend and Still be Observed (Plotted as a Function of Luminance of the Light Source). (After Wulfeck, Ref. 363)

SUMMARY AND INTEGRATION OF FACTS

The above discussion of the many factors involved in the determination of visual acuity, although limited, provides an indication of the range for variation of each of many parameters. It can not be too strongly emphasized, however, that it is not only the range of each parameter that is important, but also the interaction of each parameter with the other factors affecting acuity. Luxemberg and Kuehn (Ref. 226) suggests that all the parameters in the man-display system interact and each parameter should be evaluated with respect to the total system. This conclusion is unfortunate, for it means that many years of research have not produced functionally descriptive equations for specifying acuity.

Many of the earlier investigators of acuity attempted to relate the factors affecting acuity into usefully predictive tools. Cobb and Moss (Ref. 75) provided the data which were later replotted by Luckiesh (Ref. 220) in the 'acuity cube' presented in Figure 132. This figure is useful in demonstrating the relationship between visual acuity and background luminance, luminance contrast, and duration of exposure. Although it was derived from over 100,000 separate measurements, it is limited in usefulness by the limited range of values presented (for example, it has been worked out for only two brief exposure times) and by not taking into consideration the other factors affecting acuity.

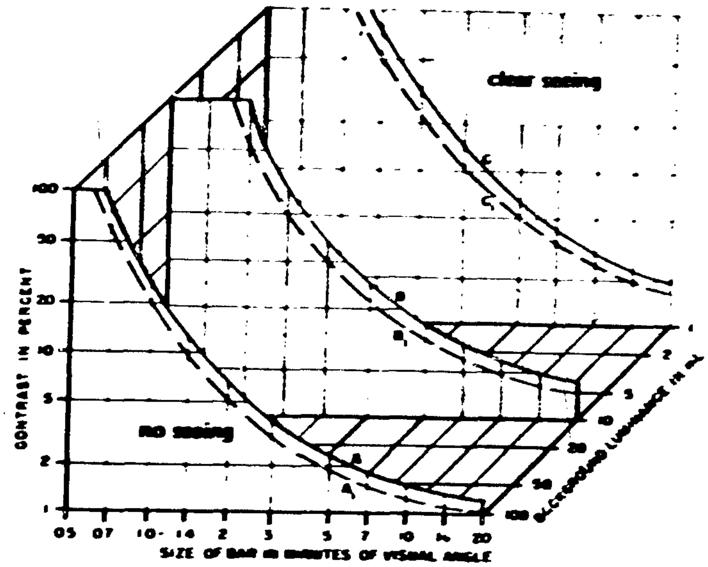


Figure 132. Interaction Between Visual Acuity, Background Luminance, Luminance Contrast, and Duration of Exposure. (After Data from Cobb and Moss, Ref. 75)

Wulfeck et al. (Ref. 363) approached the problem from a slightly different angle. In an effort to summarize the factors of visual acuity, he accumulated the "five basic curves of visual acuity" presented in Figure 133. The figures are useful in basic design. However, these basic curves fail to indicate the relationship among all of the factors of acuity and again suffer from range limitations. Additionally, the data were derived from earlier (but carefully controlled) studies conducted under laboratory conditions using low illumination levels. Modern display technology has produced displays which operate in all environments (night viewing as well as bright daylight viewing), but acuity research has consisted to a large extent only of generalizing earlier results to the new display situation. What is required is a new series of 'basic acuity' studies conducted under operational conditions with a full range of environmental factors accounted for including stress, vibration, intense illumination and visual fatigue.

A major difficulty with both of the above described efforts is the fact that they do not relate acuity factors to specific task performance. Acuity is regarded as almost being the end in itself rather than a description of the limiting characteristics of the eye as a sensor. Once these limiting characteristics have been established, they need to be related to the operation tasks that must be performed. The fact that the eye can detect a point source of light subtending 0.5 second of arc is of little value in aligning pointers, or the fact that the eye can resolve detail as small as 0.5 minute of arc does not

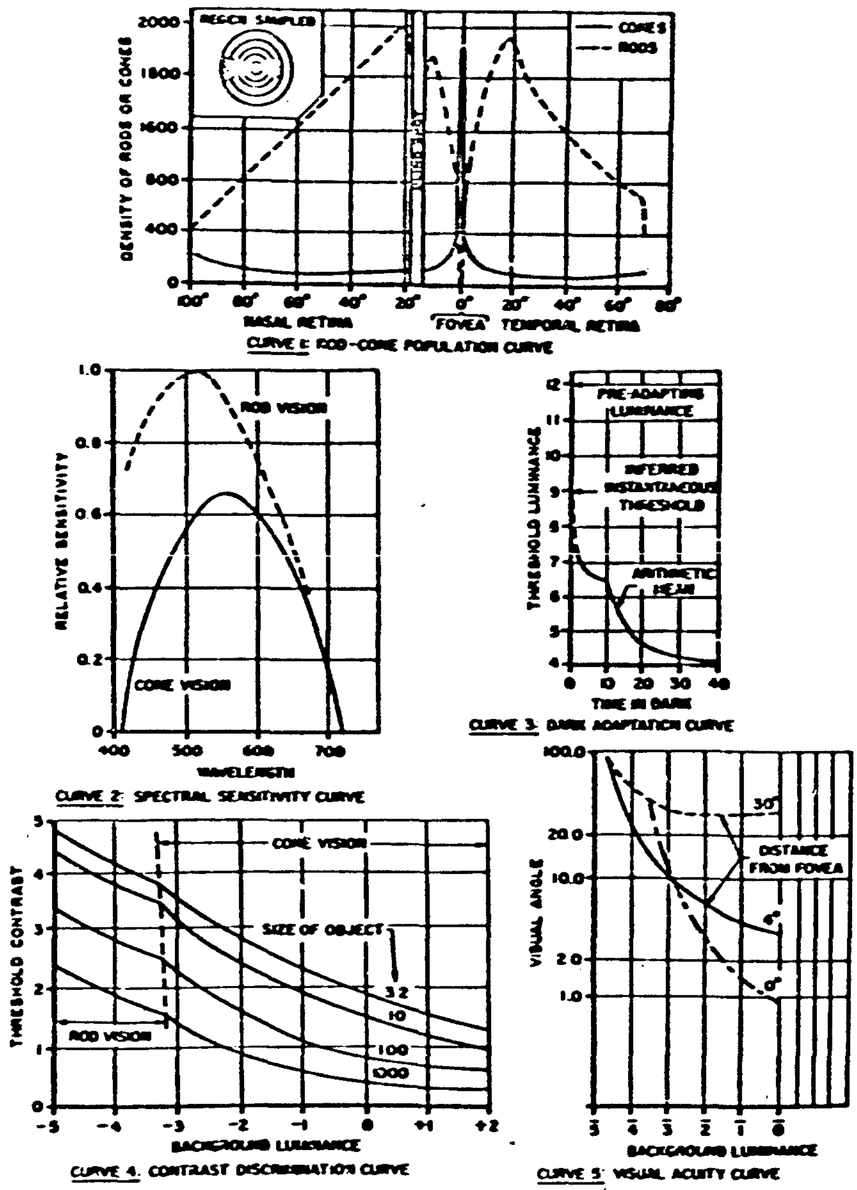


Figure 133. The Five Basic Curves Related to Visual Acuity. (After Wulfeck et al., Ref. 363)

tell the designer how much imagery resolution must be achieved in order for the pilot to detect a specific structure with 100% accuracy. The existing base of academic research is probably adequate to supply this needed information; however, weakness in the data are the lack of integration and the lack of applicability to display design.

The parameter-interaction matrix presented in Table 59 is presented in an effort to relate the different factors affecting visual acuity to specific task performance. It is, however, limited in that it only indicates the parameters affecting a given task and does not provide quantitative data for these relationships. In this respect, it is only effective as a guide to illustrate the factors affecting a given task. Identification of acuity factor-task relationships, nonetheless, is valuable in that it helps the designer become aware of all the factors that need to be considered.

Re-tabling the factors presented in Table 59 into the format presented in Table 60 shows more of the functional relationship of one parameter to other factors in the system. The effects of increasing values for the factor presented in Column I are shown in columns II, III, IV, and V for other parameters. The table, again, is useful as a guide but does not present quantitative relationships. The data presented in the preceding sections do not allow for the derivation of desired quantitative relationships. It is hoped, however, that this type of data integration will be forthcoming in future research.

There is no general or universal value for visual acuity, but rather a range of values in part determined by:

a. The intensity and wavelength characteristics of the emitted (target and background) luminance and the surround luminance.

b. Contrast ratios and the level of ambient illumination.

c. Eye adaptation level.

d. Stimulus size, shape, color, and method of presentation (duration).

e. Environmental factors (stress, fatigue, vibration).

The figure of one minute of arc has been commonly accepted as the minimum value for visual acuity. However, this represents acuity under ideal conditions, and the presence of any of the above degrading factors will increase this size to two, three or more minutes or arc. Additionally, the effects of degrading environmental factors are cumulative and could possibly result in an exponential increase in the required minimum size.

Table 59. Relationship of Factors Affecting Visual Acuity.

Controlling Interacting Variables / Vision / Types of Visual Performance	Visual Acuity	Depth Discrimination	Movement Discrimination	Flicker Discrimination	Brightness Discrimination	Brightness Sensitivity	Color Discrimination	Form Discrimination
Aberration Effect	o		o	o	o		o	o
Viewing Angle	o		o	o	o		o	o
Filter Effects plus Visors	■							
Visual Fatigue	o		o		o	o	o	o
Vibration	o	o	o		o			o
Background-Surround	o		o	o	o	o		o
Stimulus Shape	o		o		o	o		o
Monocolor vs. binocolor	o	o			o			
Clutter	o	o	o				o	o
Image Movement	o	o	o	o	o	o		o
Number of Cues	o	o					o	
Viewing Distance	o	o	o	o		o	o	o
Duration Exposure	o	o	o	o	o	o	o	o
Eye Adaptation Level	o	o	o	o	o	o	o	o
Object-Background Contrast	o	o	o	o	o	o	o	o
Stimulus Color	■	o	o	o	o	o	o	
Stimulus Size	o	o	o	o	o	o	o	o
Retinal Area Stimulated	o		o	o	o	o	o	o
Illumination Level	o	o	o	o	o		o	o

Table 60. Direction of Effect Produced by Changes in Factors Affecting Visual Acuity.

Variable Changed	Decreases	Increases
Ambient Illumination (Increased)	Required Target Size (Up to Point) Duration of Exposure	Flicker Discrimination Depth Discrimination Movement Discrimination Form (Shape) Discrimination Eye Adaptation Range Aberration Effect Visual Fatigue
Contrast Ratio (Increased)	Stimulus Size Required Duration of Exposure Required	Form Discrimination Size Discrimination Fatigue Effect Overall Acuity
Emitted Display Brightness (Increased)	Eye Adaptation Range Object-Background Contrast Background-Surround Contrast	Visual Fatigue Eye Adaptation Range Aberration Effect Flicker Discrimination
Duration of Exposure (Increased)	Required Emitted Luminance Stimulus Size Stimulus-Background Contrast Visual Fatigue Total Number of Symbols Presented	Amount of Detail Resolved

Generally, however, for visual targets subtending visual angles of 1 to 3 minutes of arc, visual acuity increases rapidly as illumination is increased from 10 Ft. Lamberts up to about 40 or 50 Ft. Lamberts, after which, the increase is more gradual. For targets subtending 3 to 6 minutes of arc, acuity increases rapidly from 0.5 Ft. Lamberts up to about 5 Ft. Lamberts and then gradually increases thereafter. For objects above 5 to 6 minutes of arc, little improvement in acuity is noted at intensities above 20 Ft. Lamberts. It should be emphasized, however, that excessive illumination is no substitute for small target size. Both speed of discrimination and accuracy of discrimination will increase with increased illumination up to about 100 Ft. Lamberts; however, assuming adequate contrast, little is gained in terms of acuity with illumination levels above 50 Ft. Lamberts.

It is generally concluded that, with other factors held constant, the higher the contrast between the visual target and the display background, the smaller the visual angle required for detection and identification tasks. At low luminance levels, bright targets on dark backgrounds produce greater visual acuity, while under high illumination conditions, dark targets on bright backgrounds are more effective. At a given illumination level, smaller objects require greater contrast to be as detectable as larger targets. Extended targets are more detectable than geometric forms against a bright background, however, squares are more efficient targets with regards to area subtended.

Spherical aberration is greatest on the periphery of the eye (as when the pupil is dilated under low light levels) and least on the central portion of the fovea. Pupil constriction (as under high illumination) consequently improves the retinal image quality by reducing the effects of aberration. Additionally, light entering the central foveal area is more efficient in image formation than light entering the peripheral areas of the eye.

Chromatic aberration is greatest with hues having shorter wavelengths (blue end of the spectrum), than with hues in the yellow-green range. Since the eye accommodates to only one color at a time and hues in the yellow-green range are most easily accommodated to, hues in the short wavelength range (blues) and longer wavelength range (reds) are focused in front and to the rear of the retina respectively. Blue is the least efficient color for use on information displays, with red second and yellow-green being best. Under high illumination conditions, colors should not be used for the identification of small targets.

RESEARCH RECOMMENDATIONS

Considerable research has been conducted in the area of visual acuity and in the area of the human visual system in general. From these research efforts, a rather large visual acuity data base has been compiled. Unfortunately, a myriad of methodologies were used to derive these data. Additionally, most of these methodologies used differing experimental conditions, small and perhaps non-representative population samples, limited variable ranges, inadequate treatment of interaction effects, and non-standardized methods of reporting results. From this type of data base, it is difficult to abstract valid design oriented data that is directly applicable to electronic display situations.

Researchers and designers are frequently required to rely on existing data as a data base or starting point for new research or design problems. Unfortunately, they often have neither the time nor the resources to sift through the many conflicting data found in the literature, to find information pertinent to and valid for their requirements. Additionally, many of the existing 'handbooks' and 'guides' do not provide adequate information as to how the data were derived, nor do they provide any type of standard against which these often conflicting data might be compared. What is required is some sort of 'standardized set of values' derived for a given operational situation (i.e., simulated airborne flight display situation which includes all of the factors associated with that type of situation) against which one could compare and evaluate any given data.

This reference set of data (for electronically generated airborne displays) could be derived from a series of multi-parametric (examination of all of the parameters associated with a given display situation) experiments conducted under a standard (but operationally realistic) conditions. Actual display viewing conditions would be simulated; using the same methodology, a representative population sample, a realistic (likely to be encountered) range of parameter variations, and identical treatment of the data for each phase of the study. All the parameters affecting observer visual acuity under actual operational conditions would be so examined.

The above series of studies would be conducted in a simulated operational (cockpit) display situation into which the many environmental factors encountered with airborne displays (vibration, acceleration, fluctuating ambient illumination, glare, etc.) could be induced through the full range expected to be encountered (i.e., ambient illumination ranging from 0.1 Ft. Lamberts up to 8,000 Ft. Lamberts). Each parameter should be varied in increments small enough so as to allow it to be sensitive to resulting changes in observer acuity. Additionally, the observer should be required to perform realistic opertional-type visual tasks and psychomotor tasks in order to allow for the effect of visual time sharing.

Representative visual tasks demanded of pilot-observers include:

- Symbol discrimination, which would include absolute identification of various types of symbols under all of the interacting viewing conditions. The size of the different symbols (alphnumeric, geometric and pictorial) would be varied in order to establish 100% identification thresholds for each of the viewing conditions (normal, stress, vibration, etc.).

- Locating tasks. Location of different types of symbols under the above viewing conditions and as viewed against static or dynamic, cluttered or uniform backgrounds and in a head-up and head-down configuration.

- Identification and Response. This would include examination of minimum symbol size, shape, luminous properties and location requirements necessary for 100% positive observer performance.

The above visual tasks present a basis upon which to establish acuity measurements in terms meaningful to the display designer or the researcher. Additionally, by establishing quantitative relationships between acuity (smallest symbol required for 100% detection, discrimination, etc.) and display-environment parameters (emitted brightness, vibration, etc.), valid generalizations from one display situation to another could be made (as long as the ranges in each situation coincided).

Representative psychomotor tasks in an airborne display situation would include time-sharing and attention sharing tasks likely to be encountered in operational mode. These would include verbal communication, tracking tasks, routine adjustment tasks, monitoring tasks and perhaps emergency procedures. Acuity measures derived under these conditions would be more representative of actual operational requirements.

The literature reveals no systematic evaluation of the effect of many of the factors present in the display situation upon visual acuity. Consequently some of the more important design variables expected to be encountered would be evaluated in these studies. Representative variables and the ranges of these variables expected to be encountered in operational setting would include:

- Ambient Illumination - representative ranges expected: 0.1 Ft. Lambert up to 8,000 plus Ft. Lamberts.

- Display background luminous - head down display - 0.1 to 1,000 Ft. Lamberts, head-up display - 0.1 to 8,000 Ft. Lamberts.

- Eye Adaptation - the effects of eye adaptation to light intensities from 0.1 up to 8,000 Ft. Lamberts on visual acuity.

- Light-to-dark ratio - the effects of light-to-dark ratios from 60:1 to 1:60 on acuity as the interaction with other factors.

- Flash Rate - the effects of flash rates as short as 10^{-11} sec. up to 1 second acuity.

- Emitted Hue - the effects of different hues (wavelengths) on acuity under the above conditions.

- Retinal Area Stimulated - the effects of the different parameters in retinal area sensitivity and the maximum visual angle for presentation of critical information.

- Dynamic Acuity - effect of target and/or observer motion on basic acuity.

Examination of the effects of the above (and other) design variables on basic acuity derived in a systematic manner would allow for valid generalization to other situations and realistic design oriented trade-offs. However, they must be based on a performance measurement of 100% correct identification detection, etc.). Academic-type criteria of 50% performance threshold are not valid measures in display design considerations. This is especially true if the pilot is performing secondary tasks (tracking, verbal communications, dial reading).

The design variables to be examined in these studies would include as a minimum, the following:

1. The effects of varying display background, target, surround and ambient illumination conditions on visual acuity while observing a dynamic/static display.

2. The effects of different filtering devices (display filters, goggles, etc.) on acuity as a function of different luminous conditions.

3. The effects of various contrast ratios on visual acuity in the ambient airborne display situation.

4. The effects of the different aspects of viewing time (light-to-dark ratio, flash duration, display duty cycle, etc.) on acuity under the above ambient conditions.

5. The effects of eye adaptation on acuity as a function of high intensity luminous fluxes, high intensity display emission (certain solid-state displays) and chromatic variations in the visual environment.

6. The effects of ambient and environmental display conditions on dynamic acuity.

7. The relative efficiency of different display locations, orientations, size and possibly shape on acuity under the above conditions. (This in turn results in a study of retinal image location as it affects acuity).

8. The introduction of observer performance degrading factors (stress, fatigue, anger, fear) and environmental degrading factors (vibration, acceleration, high intensity illumination changes) and their effects on visual performance under the above conditions.

9. The introduction of task loading and its effects on observer visual performance.

SECTION VIII

DISPLAY SYSTEM RESOLUTION CONSIDERATIONS

INTRODUCTION

Display resolution is a general term, like visual acuity. Resolution is used to label the product of the interaction of a number of display system parameters. Just as with visual acuity, the quantitative measure of resolution varies with the measurement technique used. Resolution however, differs from visual acuity in at least two important aspects. One of these is the fact that a number of important display parameters can be directly controlled to affect the nature of the system interaction and consequently the resulting resolution, while the basic parameters of the eye (i.e., sensitivity range, discriminability thresholds) cannot be directly manipulated to affect visual acuity. Second, changes in certain display system variables, display brightness for example, will interact with the observer's visual system to affect visual acuity. This latter type of relationship is addressed here.

The interaction of the eye, the display and the visible light environment is a dynamic and continually changing process. Visual acuity and display resolution are in constant flux; one augmenting or counter-balancing the other at all times. Physiological factors, such as prolonged stress or visual fatigue may, for example, reduce acuity while a reduction in ambient illumination may simultaneously function to increase display resolution. This observer-display interaction is quite common, but it is especially prominent during periods of (pilot) physical or emotional stress or periods of rapidly changing environmental conditions. However, little if any research has been conducted in this area. Most research is geared to optimize acuity or resolution for a constant set of display, environment, and observer viewing conditions.

Display resolution may be expressed in terms of the human response characteristics (called visual acuity), which is the ability to discriminate fine detail in the field of view compared to normal acuity based on a standard viewing distance. Graham (Ref. 145) defined visual acuity as:

$$V = \frac{D'}{D}$$

where D' = the standard viewing distance,
D = the distance at which the minimum discernable test object subtends one minute of arc.

As mentioned in the preceeding section, an object that subtends one minute of arc at the eye has a width of about 5μ (1μ = 1 micron = 0.001 mm) on the retina and is the normalized limit of resolution (even though separations of 30 seconds of arc or less are possible). It is recalled that the size of the rods and cones in the retina range from 1.5 μ to 2.5 μ and it appears that these diameters set the lower limits on acuity (and consequently resolution). These values are arrived at, however, under optimal viewing conditions and allowances must be made for the number of acuity degrading factors in the eye itself (defraction, deflection, ocular transmitivity, intraocular ambient illumination , and irradiation) and in the stimulus environment (ambient, surround and background luminance levels, display contrast, vibration, acceleration, wavelength characteristics, size of luminance area and target dimensions and shape). In the presence of the above degrading factors, it has been suggested (Ref. 301) that the normalized value of one minute of arc derived under optimal viewing conditions should be increased to two or three minutes in the presence of significant amounts of visual degradation. Three minutes of arc corresponds to a target size of approximately .024 inch viewed at a distance of 28 inches.

With the above discussion in mind, it may be reasoned that the maximum resolution of a display system (observer plus the electronic display) is limited by the maximum acuity of the eye alone. It is possible to build electronic displays with resolution much finer than the human eye can appreciate. But, there is no evidence or logical argument to indicate that these high resolution displays will improve visual performance if the eye cannot appreciate the resolution. Resolution in excess of the eye's appreciation limit produces little in the way of gains, except additional costs. It is desirable, however, to have some margin of resolution in excess of the eye's immediate resolving power for several reasons:

a. To compensate for environmental degradation of the display

b. To compensate for other than routine system degradation factors

c. To compensate for fluxes in visual acuity

The nature and extent of the 'resolution margin' is a function of the display itself, the conditions under which it will operate, and the requirments placed on the observer and the system. One reaches a point of diminishing return, however, with resolution greatly in excess of this margin.

Specification of display resolution in terms of human performance and responses (as described above) is attractive to the person responsible for the writing of performance specifications (for the human response is the ultimate determining

factor in any system), but it is not necessarily useful to the display system designer who must translate these performance measurements into terms that can be implemented by the system's hardware. Therefore, somewhat more objective measures of system resolution are desirable, and the responsibility for establishing these measures has fallen to the display designer. Consequently, a number of objective resolution measurement techniques have been developed in an effort to quantify the expression of display system resolution. The particular measurement technique selected is, to a large extent, dependent upon the type of equipment or system for which the resolution measure is desired.

Display system resolution is operationally defined as the quantification of the smallest discernable detail presented on the display. In a CRT type display, the smallest discernable unit is the CRT tube spot size, while in a solid-state type display it is the size of the individual emitter. A number of system parameters interact to determine the size of the CRT spot and apparent size of the solid-state emitter. The factors most applicable to an evaluation of the minimum discernable unit includes:

SOLID-STATE DISPLAYS

Emitter size

Emitter shape

Emitter density

Luminance intensity

Emitter edge gradient

Emitted hue

Inter-emitter gap size

Total display size

CRT TYPE DISPLAYS

Beam intensity

Phosphor crystal size

Display voltage

Emitted Hue

Channel bandwidth

Spot location on the faceplate

Screen efficiency

Faceplate optical quality

Halation effects

Method of deflection (magnetic or electrostatic)

Tube size

Number of vertical elements and raster lines

Emitted luminance level

Spot spread function

It is observed in the above lists that the factors affecting resolution are unique to the system being examined, and the interactions between these display parameters are also unique. Therefore, it is expedient to discuss CRT type display resolution separate from solid-state display resolution.

CRT Resolution

CRT resolution has been defined as the smallest discernable or measurable detail presented on the display or the spot size. Unfortunately, the measurement of CRT resolution is not so clearly defined. Carel (Ref. 58) describes no less than nine different measures of resolution and states that the values derived from each vary significantly in value and meaning. Table 61 presents a summary of these values. Each measurement technique presented in this table may be internally consistent and yield measures appropriate to some specific function. However, correlation among the various descriptions is necessary so that a standard measure may be evolved and used, regardless of the particular mode of specification. Additionally, a standard or reference value is required for effective inter-disciplinary research; for the relating of resolution values to visual acuity values.

To achieve the above, a basic understanding of the methods of measurement is required, and this in turn requires a basic appreciation of the image formation and transmission functions of the display system. Understanding of image formation and transmission, in turn, requires a basic knowledge of the parameters that ultimately affect the displayed image quality and resolution. Once this foundation is established, the road will be cleared for an attempt to relate resolution factors to visual acuity. The interdisciplinary relationship (acuity and resolution) resulting should allow for more efficacious utilization of the knowledge available in both of these areas.

It is noted that the term "basic understanding" is used here. The following discussion of resolution is for the purpose of acquainting those unfamiliar with display design with the principles and techniques used in the measurement of resolution (just as the discussion of visual acuity was to acquaint those unfamiliar with psychophysical measurement with the factors involved in the determination of acuity). For this reason, discussion will be restricted to those factors principally responsible for system resolution and will be conducted on an elementary level. Additionally, emphasis will be placed upon the interaction of the parameter examined with the system as a whole and its ultimate effect on resolution.

Table 61. Some Relationships Among Various Measures of Resolution. (From Carol, Ref. 58)

Resolution Measure	Symbol	Element or Line Pair Width	Amplitude at the Element Width	Modulation at Line Pair Separation		
				Lines or Points	Bars	Sinusoid
Radar Resolution	d	1.67σ*	.707	-.11**	-.11**	0
Equivalent Optical Resolution	s	2.83σ	.368	.27	.17	.09
Rayleigh Resolution (Optical)	p	3.08σ	.33	.39	.27	.13
Standard TV Element Width	q	$1.5\ \sigma$	.33	.37	.23	.11
TV Raster Line Width	r	2.36σ	.500	.07	0	.03
TV_{50} Element Width	w	1.67σ	.24	.50	.35	.17
60 percent Spot Size (Shrinking Raster)	u	$2\ \sigma$	.605	-.06**	-.09**	.007
Spatial Frequency at -3db MTF level	f	$7.5\ \sigma$	.001	.99	.94	.707

*σ = standard deviation, Gaussian point spread function is assumed.

** Negative number implies apparent or false resolution when object separation equals one line pair.

Organization of the CRT resolution section will be:

1. Image Formation - This includes a brief discussion of the image formation and transmission process and of the system modulation of the object point (the basic unit of information detected by the sensor device). The basis of the different pertinent measures of resolution will be discussed and related to the final presentation of the spot on the viewing screen.

2. Spot Size - The discussion of spot size includes an examination of the parameters that affect spot size and the spot sizes achievable with different equipment and techniques.

3. Video Channel Bandwidth - Brief mention is made of the effects of bandwidth on spot size and ultimately on resolution.

4. Vertical and Horizontal Resolution - This section addresses raster scanning techniques, its calculation and methods of reducing bandwidth.

Solid State Resolution

The factors affecting solid state display resolution present a number of unique relationships not necessarily found in the traditional CRT display. These variables include the emitter density, emitter size, shape, and orientation, the size of the inter-emitter gap and the rather sharp edge gradients found in the emitters. Although some generalization from CRT resolution data to solid state resolution may be possible, at least two solid state parameters have no apparent CRT display counterpart; these are the emitter shape and the size of the gap between adjacent emitters. It would appear reasonable that significantly different interaction effects would be produced by these two parameters. However, valid data directly addressing these factors have not been found. It appears that rapid advances and technical innovations geared to overcoming the physical limitations imposed by this type of display have forestalled active research geared to the examination of the effectiveness of these displays.

The rapid luminous rise and decay time and the rather sharp edge gradients associated with solid state type displays elements are phenomenon that have not been extensively (nor directly) examined in the psychophysical literature. Research remains to be conducted on the effects of high intensity, light pulses on the eye's integrating function and on the effect of using sharply defined light emitting elements separated by non-emitting areas above and below visual detection threshold. Examination will be made of data available in this area and limited conclusions will be drawn based on the sparse data available.

At the conclusion of the above two sections, an effort is made to integrate (demonstrate the relationships among) the

factors affecting visual acuity with the factors affecting display resolution. This is done to provide the reader with an overview of the total observer-display system and to provide at least an awareness of the many factors interacting on both sides of the display screen. The comments presented are general and represent 'guidelines'. They are not to be considered as absolute values and should not be generalized without due caution.

CRT DISPLAY RESOLUTION

Image Formation and Transmission

Image formation is the process of reproducing the signal intensity pattern of object space, to scale, in the image plane. In other words, the object being scanned by the sensor is reduced to a series of information points which are then transmitted sequentially to the display where they are again reconstructed into image of the original object. In an 'Ideal System', the intensity of each image point is an exact proportional representation of its corresponding object point. Also, ideally, there is no interaction among adjacent image elements. This, however, is beyond the state-of-the-art for all known sensor-display systems. In actual operation, the signal representing each object point experiences a distortion while proceeding through the system so that the image is not a series of points, but rather a series of "blurs" (Figure 135). These blurs are most intense at the image point (geometrical center) and extend over the entire image plane. When the sensor display system contains a number of factors which operate serially on the signal, the aggregate point spread function displays a propensity to approximate a Gaussian distribution. Carel (Ref. 58) has graphically represented a typical distribution (Figure 136), but this is not to imply that the function is always symmetrical and invariant across the image plane. The exact shape of the point spread function is dependent upon the physical parameters of the entire sensor display system.

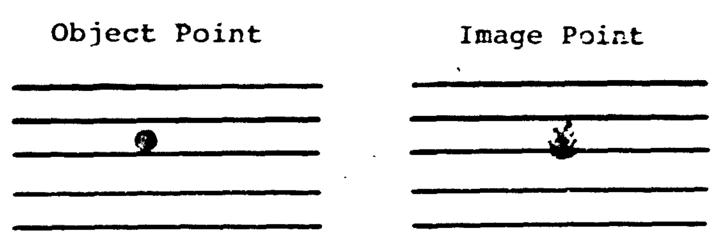


Figure 135. Object Point to Image Point Spread.

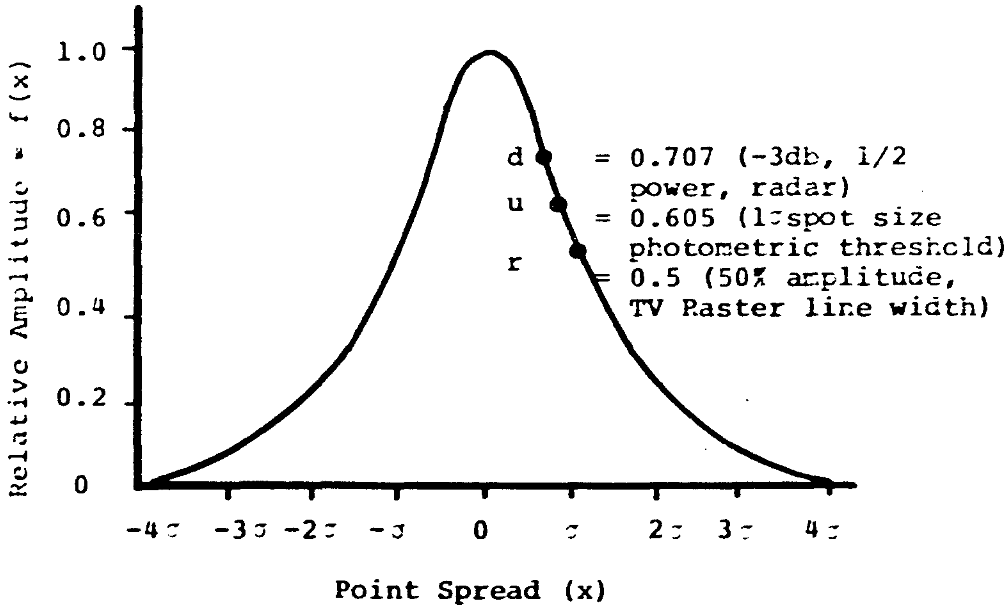


Figure 136. Normal Spread Function. (From Carel, Ref. 58).

The point spread function can be mathematically expressed by the equation:

Point Spread Function = f(u)

where: u is the distance between (separation of) the object and the image point, (distance object point transmitted) and

f is the degree of system distortion of the point in the transmission of the point from the object to the image.

The degree of system interaction (i(u)) is a function of the signal strength of the object point, the system point spread function and the distance between the object and image points. This can be expressed mathematically by:

$$i(u) = k\ f\ (u)\ I_o$$

where: f(u) is the point spread function,

I_o is the object point intensity,

u is the distance separation of the object and image point, and

k is an intensity scale factor.

It can be reasoned that the total intensity at an image point is the sum of the contributions of all the discrete object points; in the limit this reduces to the convolutional integral:

$$I(x', y') = K \int_{-\infty}^{\infty} I(x, y) f(x' - x, y' - y) \, dx \, dy$$

$$= K \int_{-\infty}^{\infty} I(x' - x, y' - y) f(x,y) \, dx \, dy$$

where: $f(x,y)$ is the two dimension point spread function,

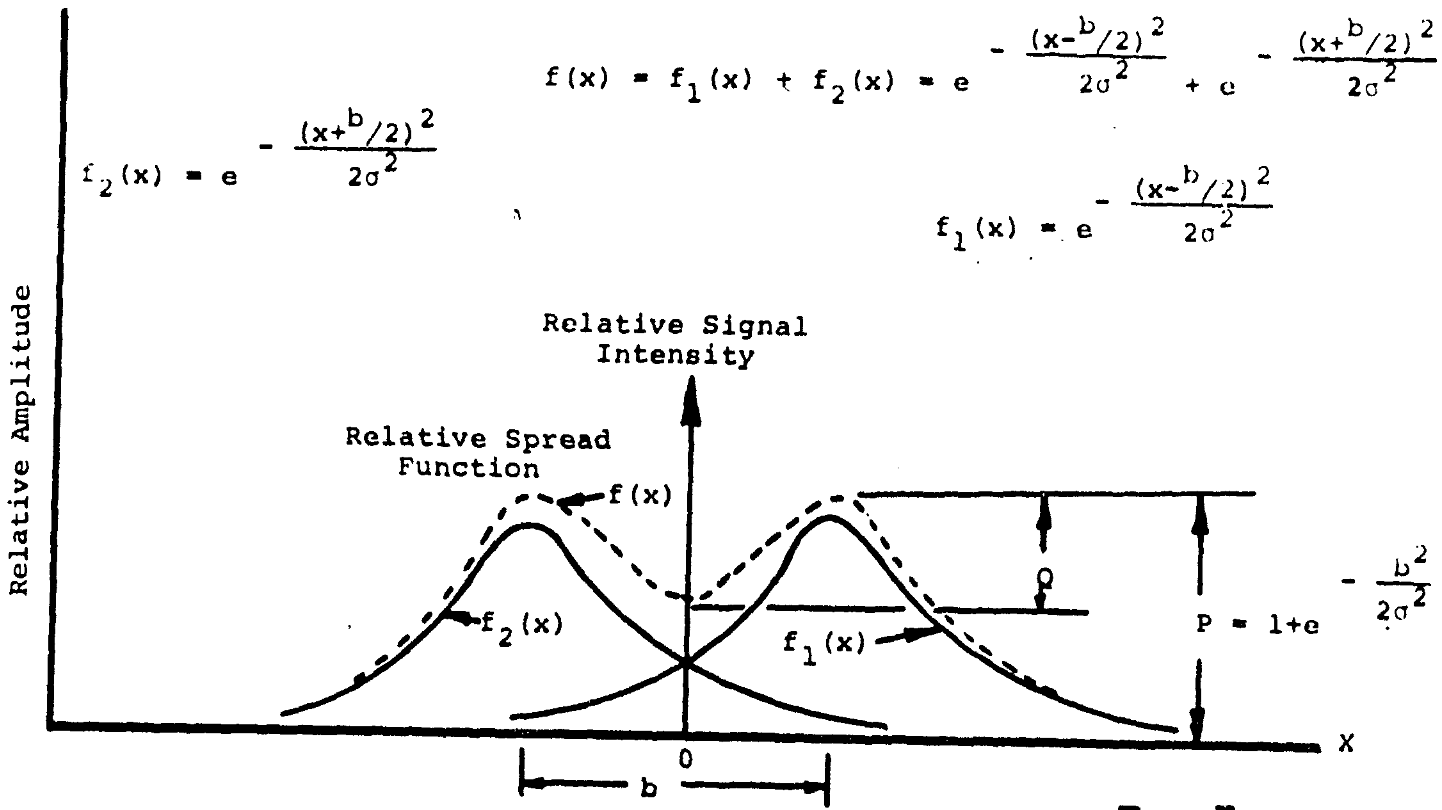
$I(x,y)$ is the signal distribution over object space,

K is an intensity scale factor,

x', y' are the coordinates of an image point, an integration over all object (or image) space is indicated.

The latter equation indicates that signal interaction is strongest when the point separation is smallest, and when the space between two points is infinitesimally small, their images are indistinguishable. As these two points separate in an otherwise uniform background, a decrease in intensity will occur between their two geometric centers. This is illustrated in Figure 137. Sawtelle (Ref. 288) notes that the basis for one definition of resolution is when the decrease becomes consistently noticeable. This definition, however, includes observer judgement which is undesirable as an objective measure. For this reason, it has become customary to define resolution as the point separation at which the contrast between the dip and the peak is equal to an arbitrary value. This process is commonly known as modulation. Three criterion values for modulation are frequently used: 50% for television, 26.5% which corresponds to the Rayleigh criterion for optical resolution, and the photometric threshold for the human eye which is taken as a value ranging from one to twenty. Resolution, or more precisely its quantitative expression, is determined by reading off the spatial frequency (or line separation) at which one of the above modulation criteria are satisfied. The criterion used will determine the numeric quantity for the resolution of that system at that given time.

A number of other measures of resolution have been developed in addition to the three mentioned above. Many of these, however, are restricted to certain types of systems and are not directly applicable to airborne electronic displays. Slocum et al. (Ref. 312) compiled a conversion table showing the



$$\text{Relative Modulation} = M = \frac{Q}{P} = 1 - \frac{2\exp\left[\frac{-b^2}{8\sigma^2}\right]}{1 + \exp\left[\frac{-b^2}{2\sigma^2}\right]}$$

Figure 137. Formation of the Image Point. (After Carel, Ref. 58)

relative values for some of these measures, the conversions are presented below in Table 62.

Table 62. Conversion Table for Several Measures of Display System Resolution where σ equals the S.D. (From Slocum et al., Ref. 312)

From \ To		TV Limiting	10% MTF	TV_{50}	Shrinking Raster	50% Amplitude	50% MTF	Optical	Equivalent Passband
TV Limiting	1.18σ		.80	.71	.59	.50	.44	.42	.33
10% MTF	1.47σ	1.25		.88	.74	.62	.55	.52	.42
TV_{50} (3 db)	1.67σ	1.4	1.14		.84	.71	.63	.59	.47
Shrinking Raster	2.00σ	1.7	1.36	1.2		.85	.75	.71	.56
50% Amplitude	2.35σ	2.0	1.6	1.4	1.17		.88	.83	.66
50% MTF	2.67σ	2.26	1.8	1.6	1.33	1.14		.94	.75
Optical ($^1/_e$)	2.83σ	2.4	1.9	1.7	1.4	1.2	1.06		.80
Equivalent Passband (N_e)	3.54σ	3.0	2.4	2.1	1.77	1.5	1.33	1.25	

Conversion table of various measures of display resolution (σ = standard deviation).

Carel (Ref. 58) in an effort to demonstrate the lack of standardization and agreement in the various methods of resolution measures, compiled the values presented in Table 61 to show some of the relationships among these measures. Again, the list is not exhaustive, but it does indicate the need for some effort in the area of standardization for these various values. In addition, to the table, the following mathematical expression of this relationship is given as:

$$d = 1.67\sigma = .59s = .54p = 1.11q = .71r = W = 83\mu = \frac{.221}{f_{-3db}}$$

where: d is the conventional radar resolution,

σ is the standard deviation of the spread function, assuming a Gaussian distribution,

s is the equivalent optical spot size (see discussion earlier in this section),

p is the optic l line pair resolution based on the Rayleigh criterion of 26.5%,

q is the standard TV element size (half cycle, width),

r is the raster line width (designated as 50% amplitude of the contour of the impulse response,

w is the TV_{50} element size (half cycle) expressed by 50% modulation level of the impulse pattern,

u is the 60% contour width (approximates lowest photometric threshold of the eye) and is often referred to as the Shrinking Raster method spot size, and finally,

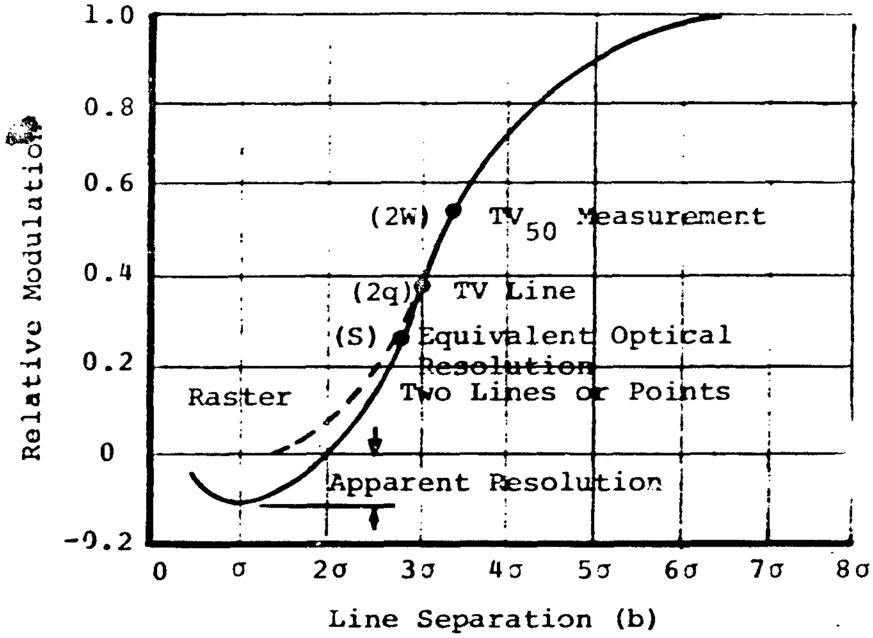
f_{-3db} corresponds to the spatial frequency at which the modulation transfer function (sine wave response) is -3db or 0.707.

This series of relationships is graphically portrayed in Figure 138.

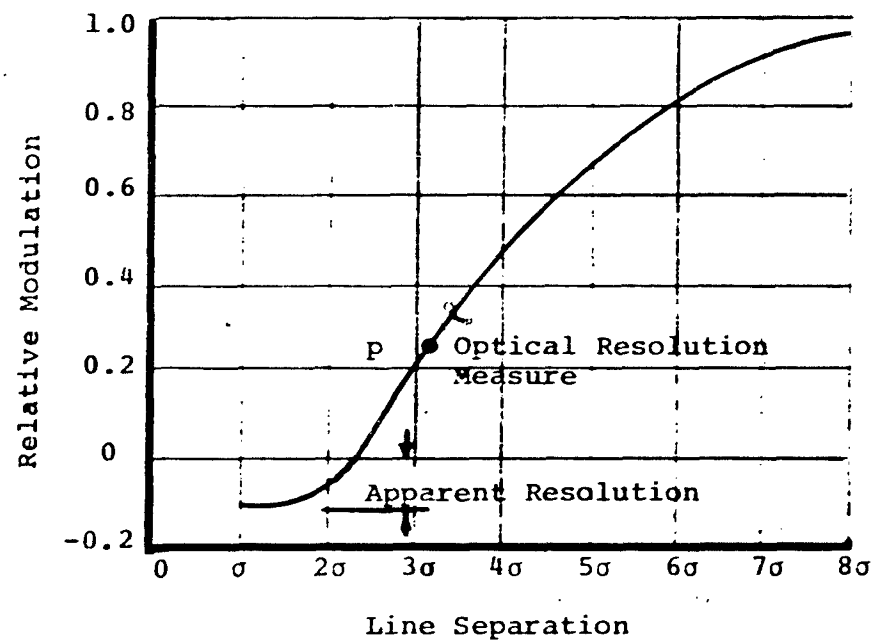
Slocum et al. (Ref. 312) also addressed the problem of resolution measurement techniques and the lack of agreement about which method should be used. These authors tend to support Carel's analysis of the problem and recommend that a method be selected as a standard. Of the various methods currently utilized, Slocum, et al. conclude that the following are most commonly used for electronic displays:

SHRINKING RASTER RESOLUTION: A raster with a known number of lines is generated on the tube face, and the vertical size is decreased until the lines disappear. At this point, the height of the raster is measured and divided by the number of lines. Slocum suggests that a trained observer normally determines this flat field condition at about two to five percent peak-to-peak light intensity variation. The energy distribution in a CRT spot is nearly a Gaussian distribution. Therefore, the flat field response factor occurs at a line spacing of approximately 2σ where σ is the spot radius at the 60% amplitude of the spot intensity distribution.

MODULATION TRANSFER FUNCTION (MTF): This is the sine wave response technique developed by O.H. Schade and analyzes the display resolution by the use of a sine wave test signal, rather than the square wave signals employed in TV test patterns. A



a. Impulse Modulation (Gaussian Spread Function)



b. Bar Pattern Modulation (Gaussian Spread Function)

Figure 133. Representation of Relationships Between Measures of Resolution. (After Carel, Ref. 58)

sine wave response test produces a curve of response called 'modulation transfer function'. When used with a device such as a scan converter video amplifier plus CRT, the MTF of the individual devices are multiplied together to determine the total system MTF. Assuming a Gaussian spot shape, if the sine wave signal were set at a half of the cycle spacing corresponding to the shrinking raster resolution line spacing, the resulting observable modulation on the display would be approximately 29% (Ref. 312).

TELEVISION RESOLUTION - TV LIMITING RESPONSE: The television wedge pattern measures spot size by determining the point where the lines of two wedges are just detectable. The number of TV lines per unit distance is then the number of black and white lines at the point of limiting resolution. Again, assuming a Gaussian spot distribution, the wedge pattern is equivalent to the square wave modulation function, and, consequently, TV resolution is frequently referred to as the limiting square wave response.

Sherr (Ref. 301) suggests that the two-slit spot measurement technique is also attractive because of the lack of ambiguity in the measurement and specification of spot size. Essentially, this method makes a 'picture' of the spot profile by moving the spot past one or two slits which are small in comparison to the spot. A photo tube on the other side of the slit is used to display the spot profile on an oscilloscope. If the time base of the oscilloscope sweep is set to correspond to the distance between the two slits in terms of spot velocity, the oscilloscope will then be calibrated in terms of the two response waveforms, and the spot width may be read directly from the oscilloscope graticule between the half amplitude points. With this method, reduction in bandwidth will cause apparent spot broadening and will result in larger readings for spot size.

In conclusion, it must be emphasized that the above measures are at best only a good approximation of the true values of the different resolutions. It can also be seen that the modulation varies as a function of the point spread function, the object separation, and the many other characteristics of the system. Any measure (true measure of threshold resolution) will have to account for these parameters in its measurements. Finally, even with the above difficulties and limitations, some measure of the total display resolution can be achieved. Slocum et al. suggests that this combined resolution can be found by taking the square root of the sum of the squares of the component resolutions (assuming a Gaussian distribution):

$$D = \quad d_1^{\,2} + d_2^{\,2} + \ldots d_n^{\,2}$$

where d_1^2 , d_2^2 ... etc. are the individual point spread functions and, D is the display resolution.

With this basic conceptualization of the image transmission and spread functions, the spot itself will now be examined.

Spot Size

The preceding discussion has addressed the formation of the spot on the faceplate of the display, the spreading of the spot (in an assumed Gaussian distribution), and several of the methods of measuring the size of the spot. A number of system parameters interact to affect the spread function and consequently the minimum spot size obtainable on the face of the display.

Luxemberg and Kuehn (Ref. 226) state that the effect of various tube parameters on electron-beam spot size on the tube screen have been largely determined experimentally. For example, by increasing the voltage on the second grid, the spot size S is reduced. Similarly, it is established that the spot size decreases with decreasing beam current (Figures 139 and 140). This is largely because of the reduction in object size in the electron optics and the decreasing aberrations in the focusing lens. A third parameter, the size of the tube itself, has been found to be directly related to the spot size. A linear relationship appears to exist between tube size and resulting spot size. Thus, by doubling the size of the tube, the minimum spot size is effectively doubled.

Another important limitation on minimum spot size is imposed by the size of the electron scanning beam itself. The electron's target requires a minimum amount of current charge before it will become excited and discharge. But, with present techniques, the current's density is also limited. Therefore, in order to obtain the required current, the beam size must often be increased. Glasford (Ref. 140) has determined that the diameter of the average scanning beam is approximately 0.005 inch. This is compared with phosphor crystal size ranging from 5 to 15 microns. (One micron = 0.000039 inch.)

Levine (Ref. 387) in a study of current beam density, developed spot sizes as a function of the tube sizes for several standard tube sizes (Table 63). These diameter/spot size relationships were based on long-persistence type phosphors with the current equal to 200 microamperes.

There are a number of non-electrical spot size determinants in addition to those considered above. One of these is obviously the characteristics of the phosphor used in the CRT itself. Davis (Ref. 103) states that the phosphor crystals used on most CRT tubes vary from 5 to 15 microns in diameter and are deposited on the faceplate in thicknesses ranging from 10 to 50 microns. These dimensions will necessarily limit the minimum area that

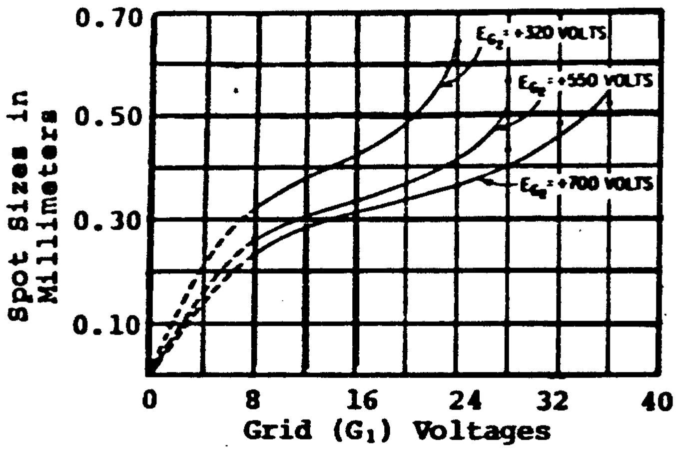


Figure 139. Display Spot Size as a Function of Grid (G_1) Voltage.

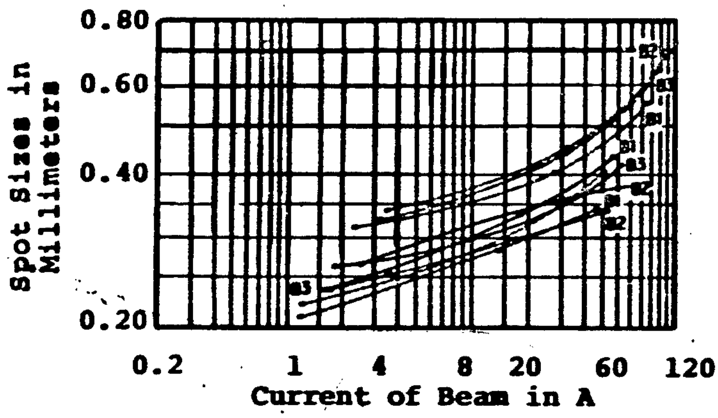


Figure 140. Display Spot Size as a Function of Beam Current for Various Sample Tubes, B_1, B_2, and B_3. (Note E_B = 7,000 Volts, E_{G_2} = +320 Volts, E_{G_2} = +550 Volts, and E_{G_2} = +700 Volts)

Table 63. Spot Sizes as a Function of Tube Sizes. (After Levine, Ref. 387)

Tube Type	Diameter	Spot Size	$\frac{K = 1.9145^*}{w}$
5FP7	5"	0.6 mm	3.19
7HP7	7"	0.85 mm	2.25
9GP7	9"	1.2 mm	1.60
9LP7	9"	1.5 mm	1.28
12DP7	12"	1.5 mm	1.28

*K = Kell Factor, w = Current

will be excited during each beam scan. The characteristics of the different phosphors will determine the amount of light that is passed to the surface of the faceplate.

The optical qualities of the faceplate (Figure 141) and the angle at which the passed rays strike the faceplate (Figure 142) determines the amount of energy that is passed or is refracted back into the tube. This refracted energy (rays) will produce the halation effect. Another consideration is the location of the spot on the face of the tube. If the spot is minimized in the center of the screen, it may increase in size as the beam moves away from the center. This "location defocusing" may be due to the differences between the center of deflection and the center of curvature of the faceplate. In order to provide uniform focus, the focus anode voltage must be varied as the spot moves away from the center position (Ref. 102).

Careful examination of the visible spot on a CRT tube reveals a light pattern around the spot produced by the electron beam. These rings of light are due to the phenomenon known as "halation" and tend to reduce the quality of the image (Figure 141). The halation effect is caused by light rays leaving the fluorescent crystals at the inner surface of the tube, traveling upward into the glass where they are refracted. Those rays making an angle greater than θ do not leave the glass when they reach the outer surface, but instead are reflected back into the glass. At each point where these reflected rays strike the fluorescent crystals, they again scatter, and it is this scattering of the rays that produces visible rings on the screen. These rings produce a hazy glow in the region surrounding the excited spot and hence reduce the maximum possible detail contrast.

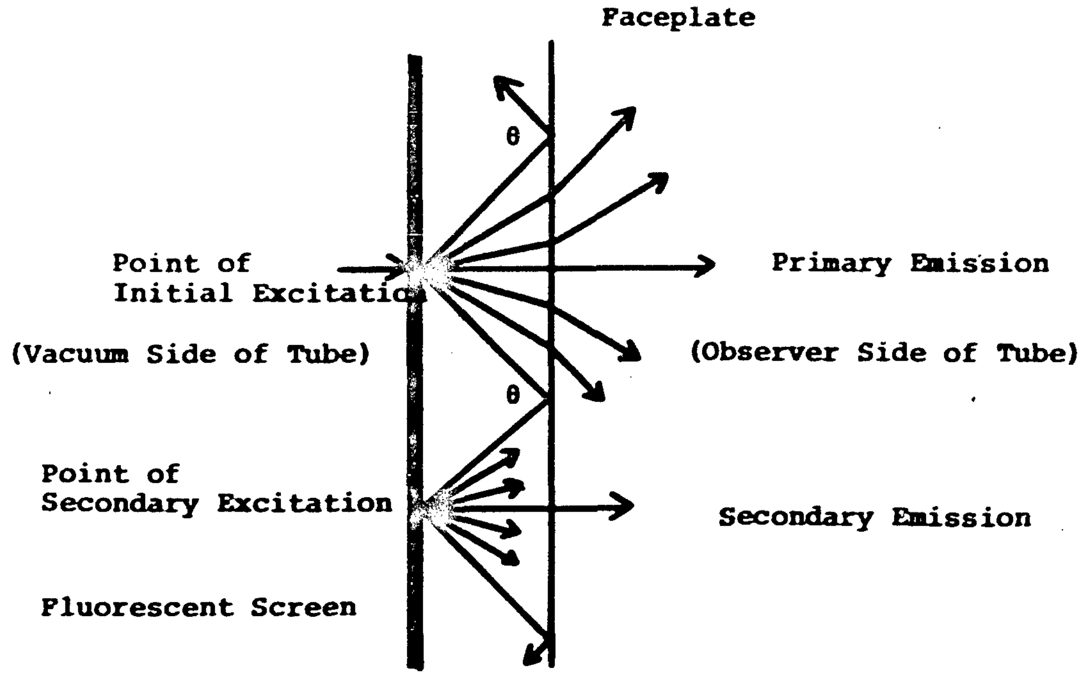


Figure 141. Halation Effect Produced by Reflection of Beams by Interior Surfaces of Faceplate.

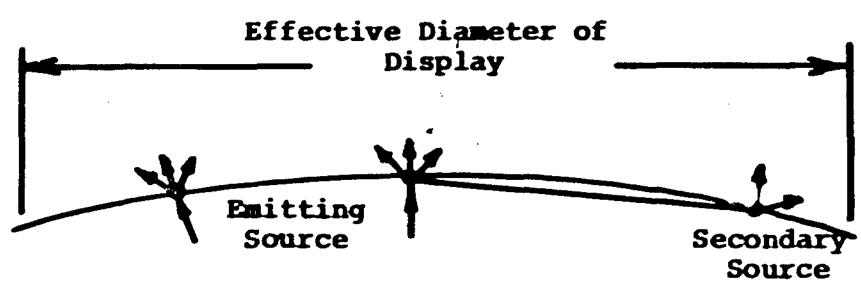


Figure 142. The Diffusion Effect Resulting from a Non-Flat Screen.

The hazy glow produced by the halation effect degrades the contrast available on the face of the CRT tube. Wurtz (Ref. 364) suggests five methods that may be used to reduce the degradation due to spot size halos:

1. Decrease the transmission qualities of the faceplate itself. Halo light passes through the faceplate at least three times (while the primary rays pass through only once) so any decrease in the faceplate transmission qualities will have a marked effect on the halo. The light available from the primary spot will, however, be sacrificed by this method.

2. Use a transparent phosphor - the limitations with this method are that the types of phosphors that can be utilized with this method are limited and again the light output is usually quite low.

3. Increase the thickness of the faceplate - the thickness of the faceplate can be increased to the point where the reflected light is reflected back to the phosphor plane out of the primary viewing area. Unfortunately, little information is available on this technique.

4. Make the faceplate very thin - the obvious problem here is that the thin plate cannot support the vacuum load. One solution to this problem is to mount the phosphor on a thin (0.020 inch) plate located behind the normal thickness faceplate. The relative fragility of the phosphor plate is often a drawback which cannot be tolerated with this technique.

5. Use fiberoptic faceplates - Wurtz recommends this method as the most effective. It is, however, the most expensive and becomes particularly unattractive for larger screen sizes.

Ultra-high resolution tubes allow an 0.8 mil spot size in the center of a 5-inch CRT (4-1/2 inch usable diameter) for a total resolution of 5400 lines (Ref. 269). Relatively high resolution tubes (approximately 4500 lines) are commercially available in any tube size.

If electrostatic deflection or duel deflection is used, spot size will increase significantly; 20 mil spot size is typical for the 5-inch electrostatic tubes, with 10 mils the minimum avaiable.

Standard phosphors permit a spot size of about 0.7 mil, measured by the shrinking raster method. Due to the difficulties in focusing a beam this small, especially in the larger tubes, it is rare to find tubes larger than 5 inches in diameter with spot sizes below 1 mil.

Generally, the magnetic deflection type CRT can offer smaller spot size and higher brightness than the electrostatic type of CRT. The "best" or smallest spot size is obtained by using magnetic focusing because less focus aberrations are presented by the magnetic field as this field does not change the electron velocity. Higher brightness is possible with the magnetic tube, since the deflection sensitivity is inversely proportional to the square root of the accelerating voltage. In electrostatic tubes, sensitivity is inversely proportional to the full accelerating voltage. Therefore, increasing the acceleration voltage to obtain higher brightness will have less effect on the magnetic deflection tube than on the electrostatic tube.

Pizzicara (Ref. 267) reports that cathode ray tubes have been developed with spot sizes as small as 0.001 inch and less. Typically, these high resolution tubes have electromagnetic deflection and focus, and extreme care must be exercised in their construction. They must be constructed with exceptionally uniform, fine grain, low noise phosphor deposited on optical quality faceplates.

To achieve these exacting spot sizes, the power supply for the tubes and coils must be tightly regulated. But the development of these newer (but lower sensitivity) recording materials require increased light output of the recording CRTs to achieve exposure in a reasonable amount of time. This increase in power, however, results in spot size growth and the resultant loss of resolution.

Channel Bandwidth

Bandwidth, the information carrying potential of the display system, directly affects the resolution of the display. Increasing the number of information bits carried and displayed by the system without increasing the bandwidth will result in a reduction of display resolution (i.e., greater spreading of the spot). The calculation of bandwidth is based on:

$f = \frac{n_a N}{2}$ = Information or video frequency

N = Scan rate (frames/second)

$n^2 = R_H R_V$ = Total number of display elements (active and inactive)

n_a = The number of active elements per line (horizontal)

R_t = Scanned lines/frame

ρ = Aspect ratio

R_V = Vertical resolution

k = Kell factor

R_H = Horizontal Resolution
= Kn_a = Total number of horizontal resolution elements

where: $K = \frac{\text{Total Number of Elements}}{\text{Number of active elements (Trace)}}$ (Note $k>1$)

and bandwidth is specified as:

$BW = f_{cz} - f_{cl}$ = Bandwidth

where: f_{cz} = upper cutoff (3db) frequency) and

f_{cl} = lower cutoff (3db) frequency)

and: $f_{cl} \cong 0Hz$,

therefore: $BW \cong f_{cz}$

Zworykin (Ref. 366) has shown that the video channel transmits a band of frequencies from approximately zero to the upper frequency given by:

$$f_{cz} = An^2N$$

where: A = Aspect Ratio = $\frac{\text{Element Width}}{\text{Element Height}}$

N = Refresh rate in frames/second (which includes interlace factor if one is present)

Since the number of picture elements (n^2) is the product of the transverse resolution (scan lines) times the number of picture elements per line, it is seen that:

$$n^2 = R_t n_a$$

Substituting the equation

$R_h = Kn_a$ (which gives the transverse resolution)

in the above equation (noting that by definition $n_a = R_h$), the longitudinal resolution (R_L) obtained is:

$$n^2 = Kn_z R_L$$

and by combining, the result shown that:

$$f_{cz} = pKn_a R_L N$$

where: p is the aspect ratio,

which indicates that for a given set of scanning conditions, the longitudinal resolution and the bandwidth upper cutoff frequency are directly proportional.

D'Aiuto (Ref. 98) using a similar equation plotted resolution n (number of scan lines) as a function of bandwidth BW (video frequency) and frame rate N: Assuming a Kell factor of k = 0.85 and an aspect ratio (p) of 1, the graphs are as presented in Figures 143, 144 and 145.

Luxemberg notes that many attempts have been made to reduce bandwidth due to the psychophysical phenomena of flicker (see section on flicker). Commercial television has achieved bandwidth reduction through the use of interlacing scan lines. In this technique, one frame actually consists of two distinct fields, each of which consists of lines spaced to lie between those of the alternate field. The total number of resolution elements is the same, but the eye is unaware of the reduction of transverse resolution in each field (which has a period of $2/R_v$) and experiences an effective flicker frequency of $N/2$. Consequently, to achieve a desired flicker free rate:

R_V may be doubled and

N may be halved without changing f_{cz}

where: R_V = Vertical resolution
N = Scan rate (frames/second)

Deutsch (Ref. 106) attempted to reduce bandwidth without sacrificing flicker free performance by using a "pseudo-random dot scan" technique. This technique has reduced frame rates satisfactorily to as low as 1 or 2 hertz. In essence, the image is a mosaic of isolated picture elements. Although this random pattern is theoretically possible, Luxemberg concludes that practical implementation is burdensome.

Humes and Bauerschmidt (Ref. 175) suggested the following equation for determination of bandwidth:

$$f_{cz} = \frac{(\text{RASI})\ (\text{Rbsl})\ (\text{frame rate})\ (\text{scan line length/raster height})}{1.2}$$

in which RASI = number of TV resolution elements along a scan line, Rbsl = number of television elements across the raster, and the assumed Kell factor is 0.7.

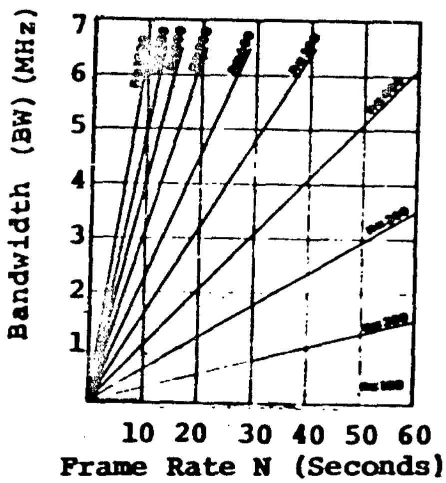


Figure 143. Resolution (n = number of Scan Lines) as a Function of Bandwidth (f_m) and Frame Rate (N). (After Ref. 98)

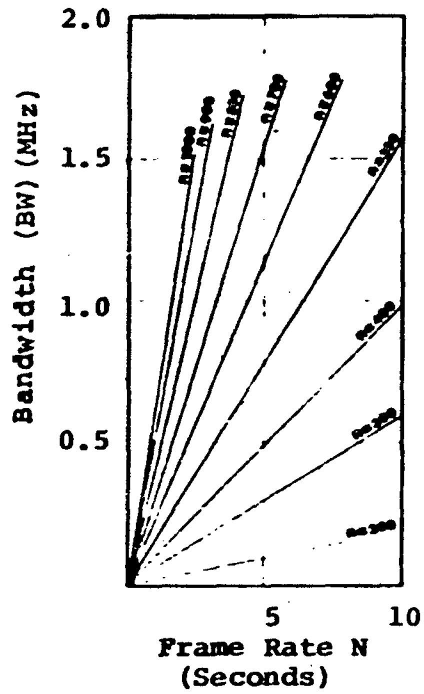


Figure 144. Resolution as a Function of Bandwidth and Frame Rate (N).

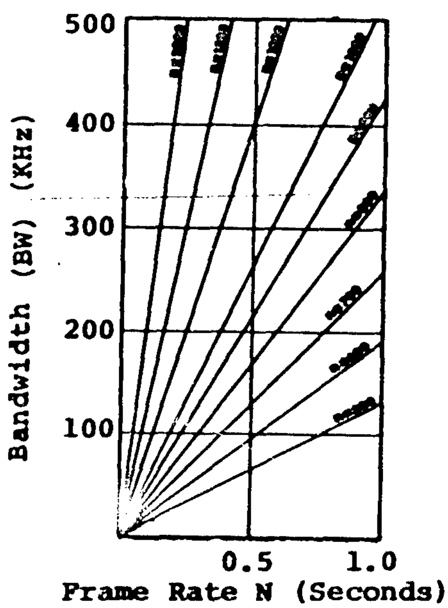


Figure 145. Resolution as a Function of Bandwidth and Frame Rate (N).

Meister and Sullivan (Ref. 232) stated that the commercial television bandwidth is approximately 4 MHZ, and they referenced Humes and Bauerschmidt as stating that high resolution TV systems have achieved as much as 25 MHZ.

Vertical and Horizontal Resolution

Disregarding for the moment the numerous technical methods of describing resolution, it is common practice to discuss raster generated resolution in terms of the total number of raster lines in the display or the total number of raster lines per unit of display surface. Luxemberg and Kuehn (Ref. 226) state that there are two basic distinctions that can be made concerning the method of presentation of raster lines. This distinction is made between rasters that are regularly repeated at prescribed time intervals, and those that are randomly or quasi-randomly repeated. When the line generation is predictably repetitive, the process is generally known as "scanning" and when it is random it is generally known as "line written".

Raster scanning consists of a repetitive series of horizontal lines placed one above the other on the viewing screen by sweeping the electron beam from side to side (see Figure 146). Information is produced by intensifying portions of the horizontal lines in response to input commands. When each horizontal line reaches its limit and one edge of the screen, it retraces back to the starting point. When the bottom horizontal line is generated, the beam retraces back to the original starting point. The beam is blank during these retraces and consequently does not produce an image on the screen.

Images that are dissected, initially formed or reformed by the scanning process exhibit a fine structure which is anisotropic. Assuming that the image is composed of a multitude of arbitrarily small picture elements centered in the scanning aperture and that these elements are alternatively black and white and arranged to form a line transverse to the scanning line, it can be seen that

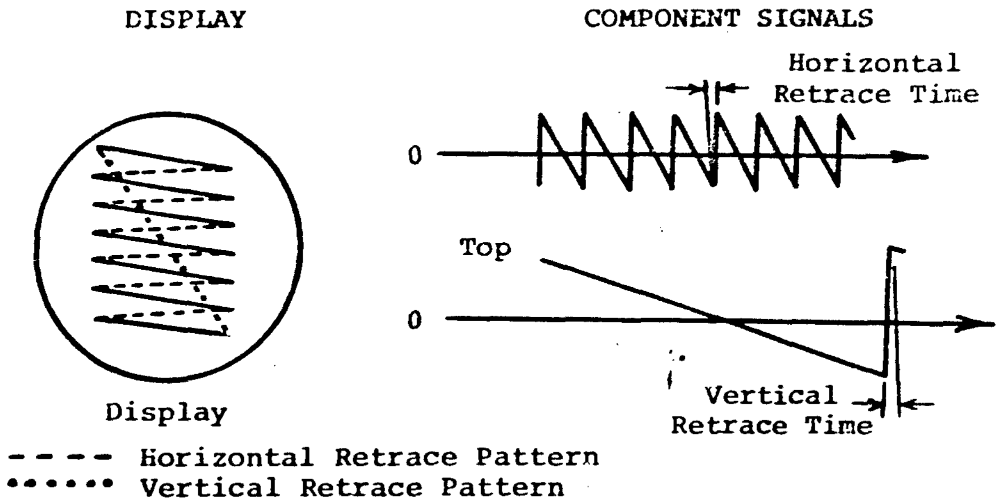


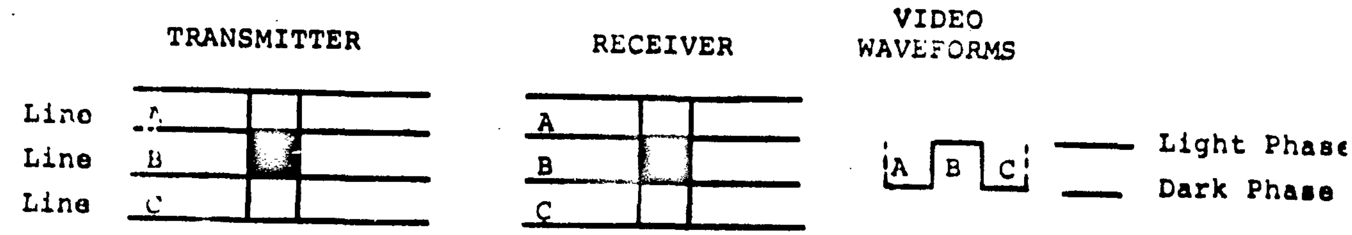
Figure 146. Typical Raster Scanned Display and Component Signals.

at best each scanning line can sample but one picture element in the transverse line image. Thus, the limiting transverse resolution in terms of picture elements is given by the number of scanning lines in the raster. Luxemberg hence indirectly defines the "picture element" as the least geometrical detail that can be discerned. But, not all the scanning lines in a raster are available to form the image because the returning raster must have their retraces obscured, and the lines used for this purpose are not available for image structure. The remaining "active" lines are the only ones determining transverse resolution (Figure 147).

If the individual picture elements were placed in such a fashion that each is covered by half of the two adjacent scanning lines, the individual elements would disappear into an unsegmented gray line. In practice, however, picture information is not nearly this uniform, and a random fine grain structure results that has a random relationship to the scanning pattern. Consequently, transverse resolution actually achieved is given by

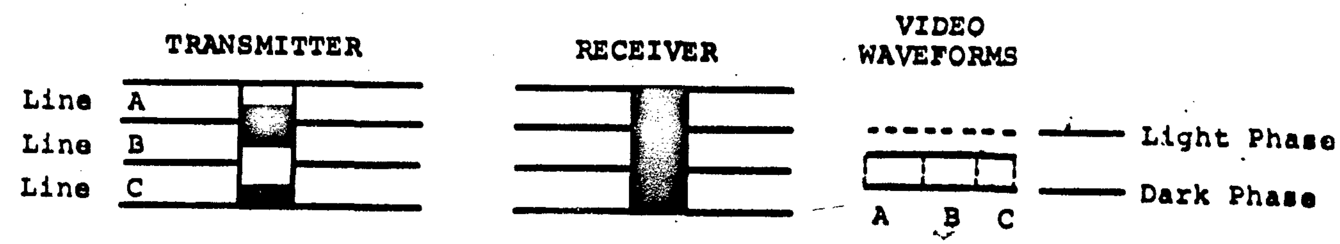
$$R_h = kn_a$$

where n_a is the number of active scanning lines and k is the "Kell factor" determined by the statistical geometry of the image covered by the raster. Television standards orient the rasters such that $R_h = R_v$ with R_v representing vertical resolution (scanning lines being "horizontal"). These Kell factors have ranged from 0.53 to 0.85. Commercial television standards are set at 0.70.



Alternate Dark and Light "Elements"

a. Scanning lines of transmitter, receiver and video waveforms in synchronism while transmitting alternate dark and light picture "elements".



b. Scanning lines of transmitter, receiver, and video waveforms not in synchronism while transmitting alternate dark and light picture "elements". The waveform indicates the "averaging of luminance" which results in the loss of detail at the receiver.

Figure 147. Typical Scanning Lines Showing Alternating Dark and Light Picture "Elements" Transmitted in (a.) and out (b.) of Synchronism.

In an effort to conserve bandwidth without sacrificing freedom from flicker, standard television employs a system of interlaced scanning (see Figure 148). The sensation of flicker in a display is, among other things, a function of the frequency of illumination of the screen. It is not a function of the number of scanning lines nor the frequency of the recurrence of a particular line itself (Chinn, Ref. 397). Therefore, a system that causes the entire area of the screen to be illuminated at a higher rate, even though the same lines are not scanned during successive cycles, results in greater freedom from flicker. The standard TV 2-1 interlace scheme does exactly this. Alternate lines are scanned consecutively from top to bottom as a group. The intervening lines form the second group and are scanned during the next scanning cycle. As a consequence, 262 1/2 lines are scanned per frame in the standard 525 line system.

Horizontal resolution requirements for raster generated displays is calculated by multiplying active scanning time (in microseconds) by the bandwidth (in megacycles) and their product by a multiplier of 2 (which is basic to all information content equations). The multiplier 2 is necessary because each cycle has a minimum and a maximum state, which in the case of video means light or dark picture elements. Ketchel and Jenney (Ref. 206) offer the following example:

Total scanning time	63.5 μsec
Blanking time	-12.0 μsec
Active scanning time (T)	51.5 μsec
Bandwidth (B)	3.0 megacycles

Inserting these values into the formula suggested by Beste (Ref. 396) for calculating horizontal resolution (N):

$$N = 2\ (TB)$$

$$N = 2\ (51.5 \text{ usec} \times 3.0 \text{ megacyles})$$

$$N = 2\ (154.5 \text{ cycles})$$

$$N = 309 \text{ elements resolvable horizontally.}$$

This method is very much simplified for the purpose of illustration. For a more detailed explanation see Refs. 58, 102, 120 and 140.

Fink (Ref. 120) suggests that a truer measure of television resolution could be obtained not from vertical or horizontal resolution alone, but from the product of both of these values. This product would be proportional to the total number of resolvable picture elements in the image.

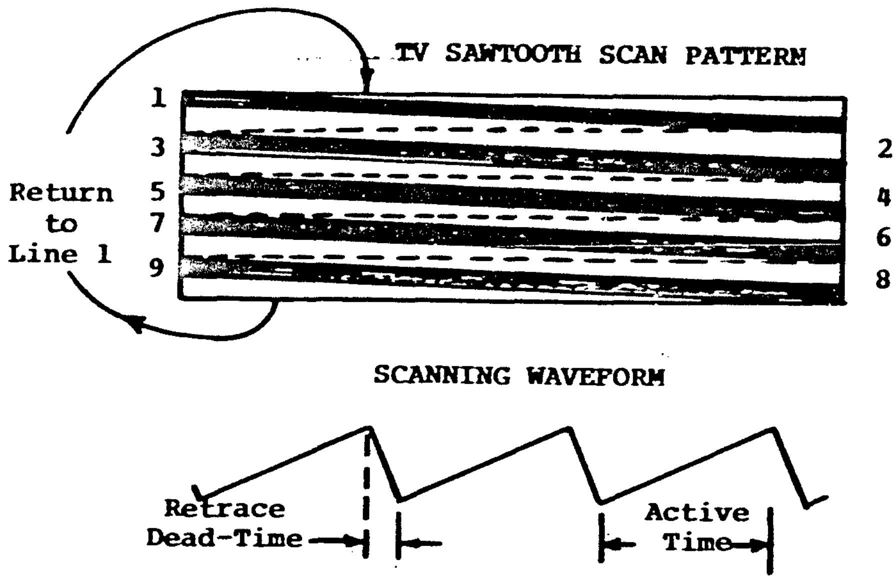


Figure 148. Typical Television Frame Interlacing.

Glasford (Ref. 140) points out that in the conventional 525 line interlaced system, 262 1/2 lines are scanned during each vertical frame (sweep). If the vertical field frequency f_v is 60 cps, the frame frequency f_f is 30 cps and the horizontal line frequency f_h is 60 then 525 lines = 15,750 Hertz. Additionally, any number of fields may be interlaced to make up a given frame. This can be calculated by letting N represent the number of fields per frame,

$$N = \frac{f_v}{f_f}$$ where: f_v = Vertical field scanning frequency
and: f_f is the frame frequency

the total number of lines n is found by

$$N = N(W + \frac{1}{N})$$ where: $W \cong$ approximately 1/3 of total number of scan lines

and the horizontal scanning frequency is given by

$$f_h = nf_f = \frac{nf_v}{N}$$

Line Written Display Resolution

Ketchel and Jenney (Ref. 206) reviewed the literature and concluded that line written display resolution does not represent a formidable problem for electro-optical display designers. They also noted that the major aircraft application of this type of display is in the head-up display. It is noted, however, that the line written technique may also be used in other types of displays. The present writers are skeptical of this over-simplification. In addition to the resolution considerations considered with the raster scan type of display, a number of unique problems are associated with the line written display, especially with the head-up display.

Ketchel and Jenney conclude that vernier alignment and the discriminability of symbols in close proximity are "the kinds of problems" which are likely to be found in such devices. They add that the symbol should be "sharp" and the lines should be wide enough to be seen against the display background. In this respect, the requirements are somewhat the reverse of those found in raster type displays. The problem is not how small the lines have to be made to improve resolution, rather how large must they be in order to ensure detection and recognition. The exact line width depends somewhat upon the precision demanded in a given display usage. The above authors suggest 3 to 5 min. arc for guidance purposes. For direct view, this is equivalent to a line width of 0.024 to 0.040 inches at a viewing distance of 28 inches.

Summary

This cursory treatment of the subject of resolution was intended to demonstrate some of the basic parameters involved in the determination of resolution. With this awareness of some of the considerations involved, it is hoped that rational decisions concerning resolution requirements in airborne displays will be facilitated. The word 'decisions' was used because it is felt that each display situation has a unique set of parameters and consequently no one decision may be applied to all situations. Each display situation places different demands on the display and these demands should be the prime determinant of the resolution required. A brief review of some of the measures of resolution currently in use or recommended indicates the following values:

Fink (Ref. 120) states that the resolution power of the human eye necessitates a minimum of about 400 horizontal lines per display and a corresponding number of vertical divisions. He also notes that different countries have adopted different standards for their commercial television systems. The U.S. and the rest of North America have a 525-line standard while England uses 405 lines, most of Western Europe and Russia have 625 as a standard with the exception of France and Belgium with 819 lines. (These values are independent of screen size.)

Carel (Ref. 58) after careful consideration, recommended that a minimum of 1,000 lines be used as a standard. This in part would help to compensate for image degradation due to the multitude of parameters affecting resolution. Assuming similar raster size and 80 blanked lines (for retracing) this figure amounts to about 115 lines per inch or almost twice the number of lines found in the average 1967 display (Ref. 206). On the assumption that the eye's resolving power is limited to about one minute of arc, Carel's display recommendation would approach the limits of the eye. (One minute of arc is equivalent to 120 lines viewed at 28 inches).

Ketchel and Jenney (Ref. 206) reviewed the literature and concluded that contemporary vertical situation displays were being designed with vertical active raster lines totaling between 500 and 700 lines on 8-inch raster displays. This is equivalent to 62 to 87 vertical lines per inch respectively. These authors expressed concern that the 1,000 lines recommended by Carel (Ref. 58) was warranted.

Whitham (Ref. 352) studied display size and resolution of displays for both a 500 line and 1,000 line system. From the information on his graph for a 1,000 line system having a height of 5 inches it is seen that the maximum element size is about 0.004 inches (4 mils) and for the 500 line system the maximum element size doubles to about 0.008 inches. At a viewing distance of 28 inches, his charts indicate that if the elements are between 0.009 and 0.085 inch, they are within the limits of acuity (which was undefined). In this case, it may be seen that the 1,000 line system exceeds the acuity criterion set by the author. However, he did not specify a particular recommendation.

Slocum et al. (Ref. 312) state that mission requirements determine the sensors to be used, and the pilot's tasks likewise vary as a function of the mission. In order to fulfill his mission, the pilot must have certain information presented to him in legible form. This in turn dictates the resolution requirements of the display. After consideration of the high resolution sensor performance, operator tasks and system performance requirements, the Slocum et al. concluded that a 1,000 TV line* display would provide the adequate resolution. They note that this would be especially desirable on a combined sensor display to minimize the loss of resolution on this type of display.

Poole (Ref. 268) noted that the assumed resolving power of the eye is about 1 minute of arc. He concluded that a display of about 115 lines per inch approaches that limit. This is approximately equivalent to a 1,000 line display (1 min of arc = 120 raster lines viewed at 28 inches). Poole adds that this 1

* 1,000 TV lines = 590 optical line pairs = 840 shrinking raster lines.

min. of arc figure is an approximation and should not be taken as the only basis.

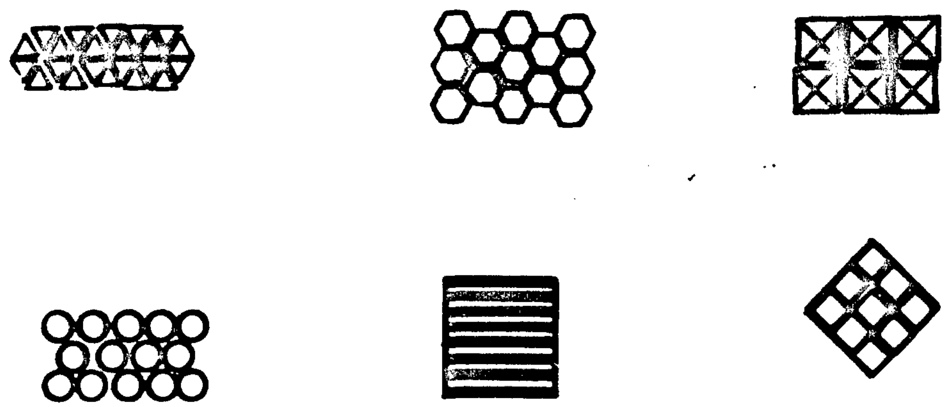
Chinn (1953) suggests that the number of lines in a display should be determined by the resolution required from the display. By establishing the resolution requirements and accounting for the various other factors affecting resolution, the number of lines can be determined. He suggests that the number arrived at should be an odd number so that if interlacing is used to conserve bandwidth, there will be an equal number of lines (plus a fraction, i.e., 262-1/2) per field. Even-line interlacing, although possible, is not feasible because of the high degree of accuracy required.

SOLID STATE DISPLAY RESOLUTION

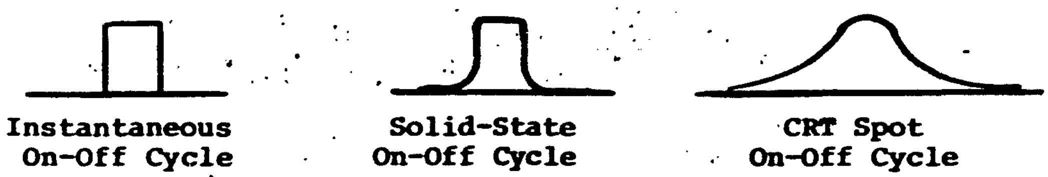
Design variables influencing X-Y matrix solid state display resolution essentially are counterparts of similar variables influencing CRT display resolution. The variables include number of vertical resolution elements, number of horizontal resolution elements, emitter size, and emitter density. One solid state variable, however, has no CRT counterpart. This variable is emitter shape. Additionally, solid state emitters are characterized by sharp edge gradients. CRT spots, on the other hand, typically are not characterized by sharp edge gradients due to the spatial luminance distribution of the CRT spot.

Variables influencing resolution and image quality factors for solid state X-Y array displays are shown in Figure 149. Because necessary research has not yet been conducted, it is difficult to identify which of the variables might have the greatest impact upon image quality. Certainly emitter size is a primary variable, but the effects of emitter size upon resolution are integrally related to emitter placement or spacing since these two factors, in turn, prescribe emitter density. Emitter placement, in turn, will be strongly influenced by the ability of engineering technology to develop solid state displays with high emitter densities, and consequently with minimal gaps or other visible spaces between emitters. Recent advances in the development of gapless electroluminescent displays have been reported (Ref. 196). Gaps between emitters were eliminated by overlapping emitter electrodes. Whether this or similar techniques can be applied to light emitting doide or gas discharge displays remains to be established. Additionally, there is the question of whether eliminating inter-emitter gaps enhances usable resolution since emitter sizes and density factors may be unaffected by such procedures.

Emitter shape is another variable over which the designer has direct control in solid state displays. Excluding segmented emitter arrays with specific application to alphanumeric



a. Representative Emitter Shapes and Configurations.



b. Representative On-Off Cycles.

Figure 149. Solid State Type Display Resolution Variables.

characters, several practical emitter shapes are shown in Figure 149. In the selection of emitter shapes, several criteria must be considered. The most important criterion is related to the type of symbology which is to be displayed. For example, round or square emitters provide considerable latitude for presenting alphanumeric or other symbols, lines, or shades of gray areas. The use of triangle or diamond emitter shapes places additional restrictions on the angles with which various symbols or lines can be smoothly displayed. However, the restrictions might be of little practical consequence if emitter sizes were sufficiently small and emitter densities sufficiently high to produce adequate resolution. With relatively large emitters (e.g., 25 to 50 mils minimum dimension), triangular or diamond emitter shapes might impose limitations upon display information content, or at least the quality with which various types of symbology could be displayed.

A second important criterion for selecting emitter shape involves the maximizing emitter area while minimizing gaps and spaces between emitters. The brightness sensitivity of the human eye is affected by area of the source of illuminance. In other words, for a given illuminance level, larger luminous objects can be detected more easily than smaller luminous objects. Indeed, one determinate of the threshold of vision is the retinal area stimulated. Consequently, if small emitters are used, the non-luminous area between emitters also should be small in order that the luminance requirements for symbols comprised of numerous activated emitters will not turn out to be influenced by single emitter dimensions rather than total symbol (family of emitter) dimensions. A review of both basic psychophysical research and design-oriented research produced no data which could be generalized with any degree of confidence for predicting symbol contrast and luminance requirements as a function of symbol size, emitter size and emitter placement or density. The necessity for such data is quite apparent.

A third criterion involving emitter shape, size and density relates directly to the level of operator task performance which is required. There are numerous criteria which may be applied to task performance. Whether the tasks require symbol discrimination, scale reading or continuous control performance, performance measures may range from those minimally required to ensure mission success to performance which allows for some margin of safety beyond minimum levels. Finally, pilot preference is directly related to display acceptance, and it is not unlikely that solid state resolution required to produce displays which are generally acceptable to pilots may exceed resolution required to produce minimally acceptable performance. Again, there are few research data which relate to pilot performance as a function of resolution for CRT or solid state displays. There are no data which directly address preferred resolution for solid state displays. One study which indirectly addressed electroluminescent display resolution and legibility is discussed below.

King et al. (Ref. 208) used a 125 segment electroluminescent bargraph display to investigate legibility contrast ratio requirements. Each EL segment comprising the bargraph was 0.25 inch wide, while stroke width for each segment was 0.035 inches. Gaps between segments were 0.005 inches. The legibility task used by King et al. required that each of 30 experimental subjects correctly read randomly determined EL bargraph values against an associated scale three times in succession. Correct readings required the accurate discrimination of on vs. off bargraph elements. The authors report that subjects could consistently achieve the accuracy needed to read the EL column against the numbered scale. Subjects also consistently reported that the 5 mil gaps between segments were easily visible. Five mils at a 28-inch viewing distance, which was used by King et al., corresponds with a visual angle of approximately 40 seconds of arc.

VISUAL ACUITY AND RESOLUTION

In the section on visual acuity, the many factors affecting the acuity of the human eye were examined and significant relationships among these parameters pointed out. In the preceding section, the factors affecting the resolution of the display screen were examined. It is, therefore, expedient at this point to attempt to relate the factors of visual acuity to the factors of resolution, where the data will permit.

Visual acuity is defined as the smallest discernible detail that the eye can resolve while display resolution is defined as the smallest discernible detail on the display face. It is recalled that the eye could reliably resolve targets as small as 30 seconds of arc (.0040 in. at 28 inches) under ideal viewing conditions, while standard CRT tube spot size is approximately 1 mil in diameter (.001 inch). Unfortunately, the minimum discernible detail that can be resolved by the eye cannot be directly correlated with the minimum spot size produced by the display, for as was indicated, a number intervening variables must be accounted for (age, contrast, illumination levels, eye adaptation). Quantitative relating of these environmental factors to either resolution or visual acuity factors have not been forwarded sufficiently to allow for the integration of all of these variables into a 'resolution system'; a quantitative step-by-step specification of the relationship of spot size to minimum visual acuity. Many of the data derived from studies of these environmental variables lack the threshold qualities of a true measure of resolution.

The diagram presented in Figure 150 has been developed in an effort to demonstrate the relationship (in graphic format) among the various factors in an information display system. It is observed that the luminance of the emitter is the medium linking the display face with the eye of the observer. It can likewise be seen that the light form emitted by the emitter is not the same light form impinging upon the retina of the observer. Not only has the form of the light been changed, but the intensity of the light has been greatly reduced (the units of light intensity are arbitrary units selected for demonstration only). Additionally, the parameters that tend to reduce the quality of the transmitted light are listed under each of the principal steps in the transmission process. It does not, however, list all of the possible factors that could interact to affect resolution.

In the absence of good hard data at all points along the 'resolution system', Table 64 is presented in an effort to demonstrate some of the possible parametric interactions and relationships. Again, this table is to be used as a guide, as all of the possible combinations are not present here. These relationships have been derived from the data reviewed in this report and represent a summation across studies where data have permitted. Because data are completely lacking on some of the parameters (or

it was felt that existing data were not valid), some "forced speculation" has been reported. On the whole, the relationships shown in Table 64, as well as those shown in Table 59 (visual acuity), are representative of the relationships affecting display system resolution. These two tables, however, do not provide an all-inclusive listing of possible factors.

CRT TYPE DISPLAY RESEARCH REQUIREMENTS

Considerable research and evaluation has been performed on electronic display equipment, on the visible light environment, and on the eye. However, little valid research has been conducted on the observer-environment-display system as a functioning unit. Operator performance studies have been conducted under laboratory conditions (low-light level to room level luminance conditions) without the presence of performance degrading environmental factors (vibration, stress, acceleration, high ambient luminance conditions). Studies of effects of the visible light environment on resolution tend to eliminate the observer from the system, while studies of display equipment eliminate either the observer or the environment. No multiparametric evaluation of the observer-environment-display resolution system under operational conditions is found in the literature. For this reason, the following general research recommendations are made (based on Figure 150 showing the total resolution system):

1. A multiparametric display-environment-observer system should be developed wherein display parameters, environmental parameters and observer viewing conditions could be examined individually and in combination with respect to their effects on the total system.

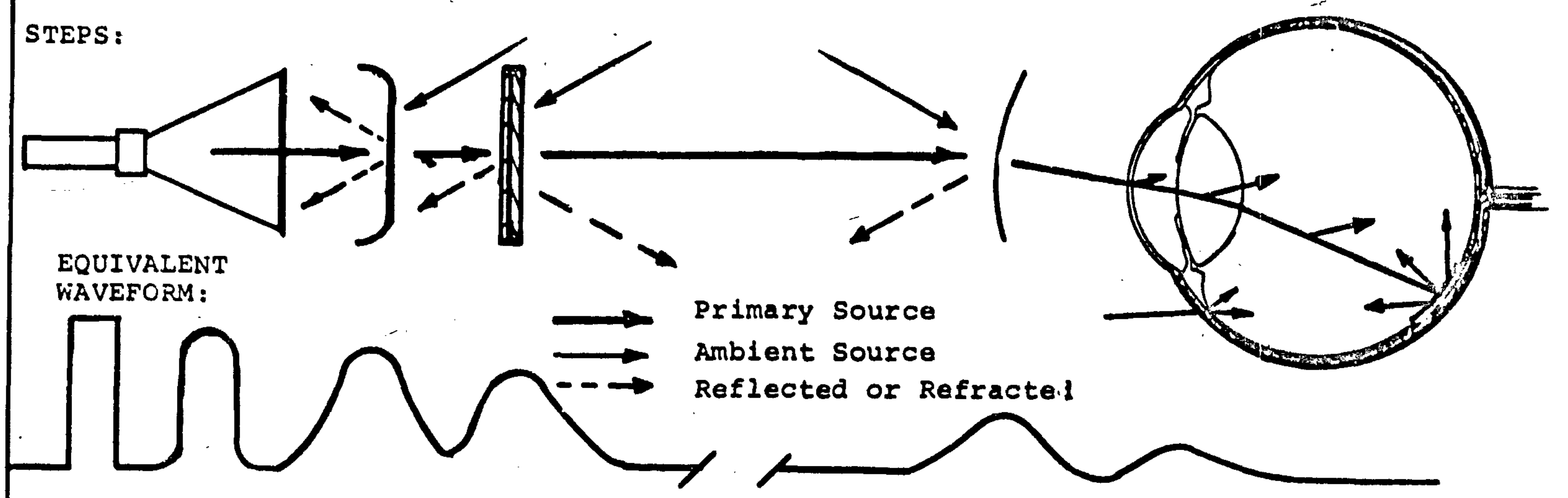
2. Using the above vehicle, a systematic evaluation of the individual (or combinations) display, environmental and observer parameters be conducted with emphasis on its effect on the overall system. Display legibility would be the performance measurement with realistic operator tasks included in the measurement.

3. Evaluation should be conducted under conditions expected to be encountered under actual operating conditions with the performance degrading factors systematically induced into the system.

4. With the data derived from the above evaluations, a quantitative display-environment-observer (and qualitative) formula should be developed that could account for the impact of each of the major factors on the total resolution system. This formulation would be beneficial as a realistic design tool for display design and display system evaluation.

PHASE	PULSED	FACE-PLATE	FILTERS	ENVIRONMENT	VISOR OR GOGGLES	INTRA-OCULAR MEDIA	VISUAL SYSTEM
TRANSMIT-TANCE RANGE		58-89%	10-50%	Variable (?)	10-20%	81% (Max.)	Variable
LIGHT-UNITS*	1,000	890	445	Variable (?)	89	75	App. 75 of original 1,000 units reach retina

STEPS:



FACTORS TO BE CONSID-ERED:	Focus Tech. Beam Diameter & Intensity	Optical Qualities Halation Refraction Thickness Phosphor	Viewing Distance & Angle Ambient Illumination Observer Time-sharing	Optical Quality Reflection Refraction	Defraction Deflection Irradiation Accommodations effect	Not Examined here

*Arbitrary Units

Figure 150. Schematic of Light Transmission Process in "Total Resolution System" from Display Surface to Eye of Observer. (Note that Environmental Degradation was not accounted for)

Table 64. Summary of Eye-Equipment System Parameter Interactions.

Eye Limitations	Visual Acuity	Retinal Area Stim.	Display Location	Cueing	Target Contrast	Ambient Illumination	Background Illumination	Field of View	Exposure Time	Task Loading	Target Size	Viewing Distance	Eye Motion	Adaptation	Chromatic Aberration	Spherical Aberration	Physiological Nystagmus	Size, Density Distribution of Retinal Cones	Defraction	Amount of Information
Amount of Info.	*		*						*	*	*		*							*
Spot Spread	*	*			*						*	*								
Line Spread	*	*			*	*					*	*								
MTF	*																			
Vibration	*	*		*	*				*		*		*							*
Bright vs. Dark Target	*	*		*	*	*	*		*			*		*	*					
"Granularity"	*																			
Deflection	*	*			*	*	*				*			*						
Halation	*	*			*	*	*				*			*						
Faceplate	*		*		*	*	*	*			*	*		*						
Screen Effec.	*		*		*	*	*				*	*		*	*	*				*
Phosphor Charac.	*				*	*	*		*		*			*	*	*	*		*	*
Spot Location	*	*	*		*	*		*	*	*	*	*	*	*	*	*	*	*	*	
Voltages	*	*			*	*	*		*											
Beam Intensity	*	*			*	*	*		*		*			*		*			*	
Wavelengths	*	*				*	*		*					*	*	*	*	*	*	
Color	*	*		*	*							*		*	*	*	*	*		*
Image Enhance.	*		*	*	*	*	*			*	*	*		*						*
Background Bri.	*	*		*	*	*								*						
Target Bright.	*	*		*	*	*	*		*	*	*	*		*	*	*	*	*	*	
Image Motion	*	*		*	*					*	*		*							*
Display Size	*	*	*	*	*	*		*			*	*			*	*	*	*	*	
Spot Size	*	*				*						*	*			*	*	*	*	
Scan Lines/Ht.	*	*			*						*	*								*
Bandwidth	*				*						*									*
Equip. Resol.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

5. Data derived from the above research should be integrated in a meaningful quantitative manner and presented in concise handbook format for use by human factors engineers as well as display design engineers. The handbook should show the nature and extent of parameter tradeoffs and their effects on the resolution of the system. The handbook should be so designed as to allow for the incorporation of new advances and research results into the existing body of information.

SOLID STATE RESOLUTION RESEARCH REQUIREMENTS

Since no directly relevant solid state X-Y matrix display resolution research data were found, the research requirements presented below should be considered, in part, as being within the context of exploratory research. The value of exploratory research is that it provides data which can be used to identify the relative degrees of importance of design variables tested, produces data which can identify trends for future research, identifies interactive variable relationships, and identifies critical tasks for use in more generalizable design-oriented research. Because of the almost total void of data directly relevant to operator task performance as a function of solid state display resolution factors, it is felt that requirements for exploratory research are most paramount. It also is felt that display device simulation, rather than operational displays, should be seriously considered in order that current state-of-the-art display hardware limitations do not limit the extent of exploratory research.

It would appear most efficient to employ display legibility tasks for investigating solid state display resolution. Such tasks could include alphanumeric and symbol identification, scale reading and simple pointer positioning tasks. Performance measures should include probability of correct symbol identifications, scale reading error and pointer positioning error, and time required to read scales and make scale settings. Additionally, because emitter density may directly influence symbol contrast and emitted luminance requirements, photometric measures defining symbol-to-display contrast should be made for studies in which emitter luminance is a variable.

Table 65 presents design variables and ranges for each variable which at this time appear to represent realistic design variable conditions for experiments relating to solid-state display resolution. As with such investigations, the interactive effects of combinations of variables must be seriously considered. Because of anticipated interactive effects, it is recommended that the following combinations of variables should be considered: symbol size, symbol type, emitter size, emitter spacing, emitter density; and symbol size, emitter size, emitter spacing, emitter density, emitter luminance; and symbol type, symbol size, emitter shape, emitter density.

Table 65. Recommendations for Variables to be Researched in the Context of Solid State Display Resolution.

Symbol Type	Alphanumerics, circles, squares, X's, crosses, scales and pointers.
Symbol Size	0.10 inches to 0.75 inches for alphanumerics and other symbols. Scale and pointer dimensions should be selected with respect to emitter size.
Emitter Size	A range of from 5% to 100% of the maximum emitter available as determined by the emitter density and emitter shape being tested.
Emitter Spacing	0.5 mils through 40 mils, with spacing to be determined in conjunction with emitter density.
Emitter Density	Five emitters per maximum symbol dimension through 75 per maximum dimension depending upon symbol size and emitted size. Matrix sizes for alphanumerics should include 3x5, 5x7, 7x9 and 9x11. Matrices comprised of greater numbers of emitters should be considered for high resolution displays incorporating larger (e.g., 0.50 inch) maximum symbol dimensions.
Emitter Shape	The reader is referred to Figure 149 for emitter shapes which appear to merit investigation.
Emitter Luminance	0.1 through 1,000 Ft. Lamberts, depending upon contrast ratio requirements.

CRT DISPLAY SYMBOL RESOLUTION REQUIREMENTS

Introduction

The literature reviewed yielded little data on target detection as a function of the two primary factors of resolution affecting legibility; the number of active scan lines per symbol height and the video bandwidth. However, some data exists on target identification as a function of these parameters. The performance measures used in generating this identification data are the probability of correctly identifying the target or symbol as a function of the number of active scan lines per symbol height and the speed of identification as a function of the number of active scan lines.

It is interesting to note that display system resolution is referred to or measured by the number of active scan lines per inch of the display surface. Displayed symbol (alphanumeric or geometric forms) legibility is normally measured in the number of active scan lines per symbol height. Both of these measures produce values that are dependent upon or, in turn, influence the total number of active scan lines per display height. A brief examination of Table 66 reveals that for any given display size (9" and 18" arbitrarily choses), the number of active scan lines per inch and the number of active scan lines per symbol height vary significantly as a function of the total number of scan lines in the display. Caution must be exercised, therefore, in the interpretation of symbol legibility as a function of the number of active scan lines per inch or per symbol height.

Table 66. Approximate Scan Line and Symbol Sizes as a Function of the Total Number of Active Scan Lines in the Display.

	Display Size	Total Number of Active Scan Lines 525	1,029	9,000
*Lines per Inch	9"	58.5	114	1,000
	18"	29.2	57	500
*Line Size per Inches	9"	1/58.5	1/114	1/1000
	18"	1/29.2	1/57	1/500
*Symbol Size @ 10 Scan Lines per Symbol Height	9"	5/29	5/51	1/100
	18"	5/14.6	5/28.5	1/50

*Approximate Values

A number of other factors are concerned with symbol resolution and consequently warrant consideration. They are, however, not the direct consequence of display system resolution and hence have been addressed in separate sections. These factors include the type and style of font used for alphanumerics (discussed in the section addressing alphanumerics), the type of geometric or pictorial symbol used (discussed in the section addressing symbolic coding), the physical construction of the symbol (visual angle subtended, stroke-width-to-height percentage also discussed in the above referenced sections), and the operator task requirements. This section, consequently, is limited to a discussion of symbol legibility as a function of the number of active scan lines per symbol height and system video bandwidth.

Other types of electronically generated display systems are not addressed in this section because of the special nature of the symbology they display and/or because of data voids.

Digitally addressed X-Y dot matrices generally discuss symbol legibility in terms of the total number of dots in the matrix (i.e. 5x7, 7x9). Consequently, legibility is expressed in terms of the percentage of correct responses as a funct . of the matrix size or configuration. The limited data available on this subject are presented in the section addressing alphanumeric matrix symbols. Line written displays (caliographic), on the other hand, have resolution and legibility parameters unique to that type of display. In a line written display, the problem is not how small the basic resolution unit (emitter size or spot size for example) must be, but how large (wide) the lines must be to be legible. Carel (Ref. 58) concludes that caliographic resolution currently presents little problem as long as the lines displayed (or symbols) are sufficiently large to be seen, but not so large as to obscure other figures and symbols on the display. The literature reveals a lack of pertinent data dealing with line written symbol legibility. Finally, solid-state symbol legibility is not considered due to the data void existing in this area.

The following discussion considers symbol resolution in terms of:

1. Number of active scan lines per symbol height

2. Quality of the equipment used (525 line displays, 1,029 line displays)

3. Video bandwidth used in the system

The resolution required for a symbol identification task varies significantly with the type of symbol used. Several of the studies reviewed have used a ,hanumeric symbols, and a comparison across studies indicate that resolution requirements are less for these types of symbols than for more real world

symbols (geometric or pictorial symbols). Additionally, the studies reviewed are relatively consistent in their findings that a vertical resolution of between 10 and 12 lines per symbol height will optimize the correct identification of alphanumeric symbols. Similar agreement is reported for geometric and pictorial symbols, with a minimum of 14 raster scan lines required per symbol height (on a 2 megacycle or higher bandwidth) for correct identification. These results were, however, derived from studies conducted under laboratory conditions with no visual or resolution degrading factors present. Use of the data presented below, therefore, is contingent upon the following conditions:

1. Display and symbol luminance and contrast are more than adequate for legibility (see sections on brightness and contrast)

2. No display signal noise was present

3. Subjects are familiar with the symbols used

4. All symbols are sufficiently large to avoid problems associated with visual threshold (see section on acuity).

Lines per Symbol Height--Alphanumerics

Using a standard 525 line Fairchild Model TC-100 Camera and a Miratel 14 inch Video Monitor, Shurtleff and Owen (Ref. 306) performed a study on the legibility of capital letters and numerals with vertical resolutions of 6, 8, 10, and 12 active scan lines per symbol height. For a complete description of the experimental variables see Table 67. An examination of Table 68 indicates for the resolutions tested that legibility varies with the performance measure considered. Figures 151, 152, 153 and 154 graphically display these relationships. The data indicate for the subjects receiving a small amount of practice (Part I), if identification time was the important consideration, then 12 active lines per symbol height should be used; if accuracy of identification was the primary consideration, then 10 lines per symbol height would be adequate. When subjects received additional practice (Part II) and identification times alone were considered, 10 lines per symbol height were sufficient; if accuracy of identification was the important factor, then as few as 8 lines per symbol height was adequate. Shurtleff and Owen concluded that a minimum of 10 lines per symbol height would be sufficient for systems applications and this is consistent with their findings.

Table 67. Experimental Conditions for Shurtleff and Owen Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 8	Horizontal Spacing: Not relevant
Visual Characteristics of Subjects: 20/20 near and far acuity; normal phoria and color.	Symbol-Background Relation: Light/Dark Symbol Brightness: 20 Ft. Lamberts Background Brightness: 1.5 Ft. Lamberts
Number of Symbols: 26 letters 10 numbers	Brightness Contrast: 1233 percent
Symbol Exposure Time: Response time to identification.	Ambient Illumination: Not stated
Symbol Font or Style: Courtney vs. Leroy	Symbol Visual Size: 11 Minutes of Arc
Symbol Width/Height: 75 percent	Viewing Distance: 36 to 64 inches
Symbol Stroke Width/Height: 17 percent	Viewing Angle: Zero degrees

Table 68. Statistically Significant Differences Between Successive Resolution Pair Comparisons for Small and Additional Practice Parts Using Average Identification Times and Accuracy of Identification as Performance Measures.

RESOLUTION PAIRS IN

LINES PER SYMBOL HEIGHT

Part I Small Amount of Practice		Part II With Additional Practice	
Average Identification Time	Accuracy of Identification	Average Identification Time	Accuracy of Identification
12[2] - 10[1]	12[2] - 10	12[2] - 10	12 - 10[2]
10[2] - 8[1]	10[2] - 8[1]	10[2] - 8[1]	10[2] - 8
8[2] - 6[1]	8[2] - 6[1]	8[2] - 6[2]	8[2] - 6[1]

[1]Statistically significant (significance level not reported) differences between the resolution pair indicated.

[2]Indicates which of the resolutions compared performed best.

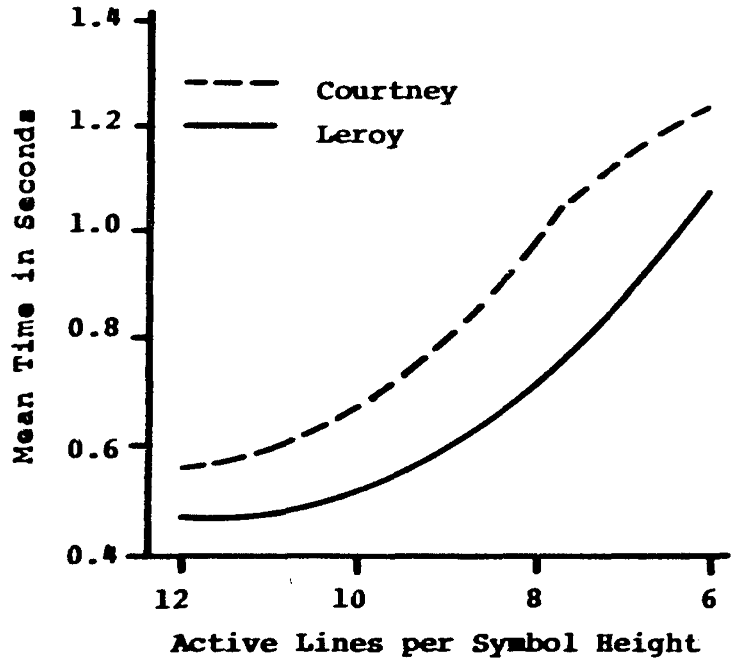


Figure 151. Average Identification Time as a Function of Vertical Resolution for the Small Amount of Practice Group, Part I. (Adapted from Ref. 306)

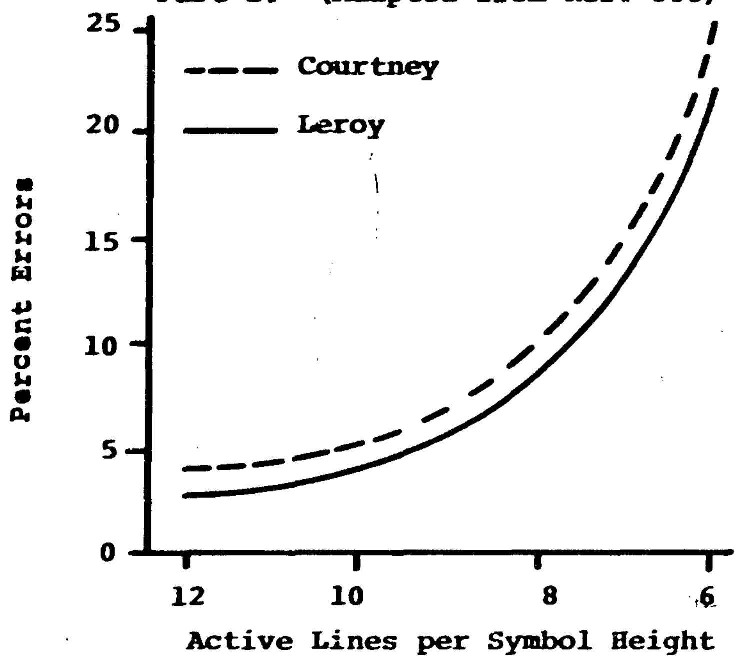


Figure 152. Identification Errors as a Function of Vertical Resolution for the Small Amount of Practice Group, Part I. (Adapted from Ref. 306)

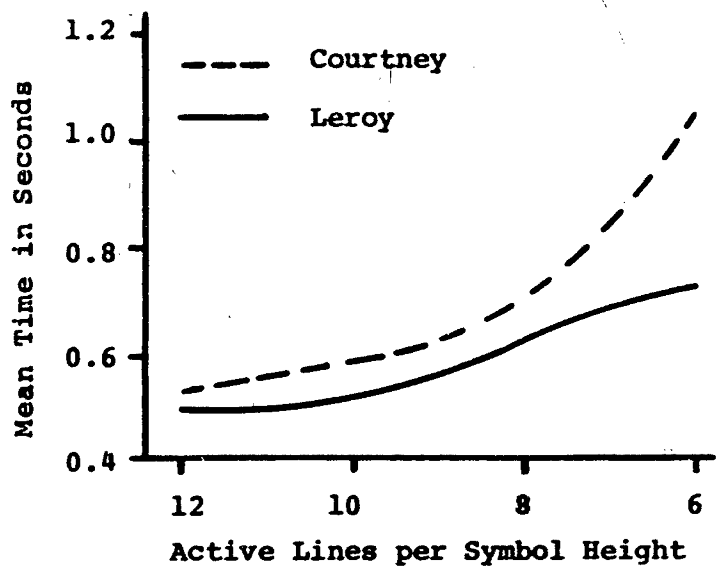


Figure 153. Average Identification Time as a Function of Resolution for the Additional Practice Group, Part II, (Adapted from Ref. 306)

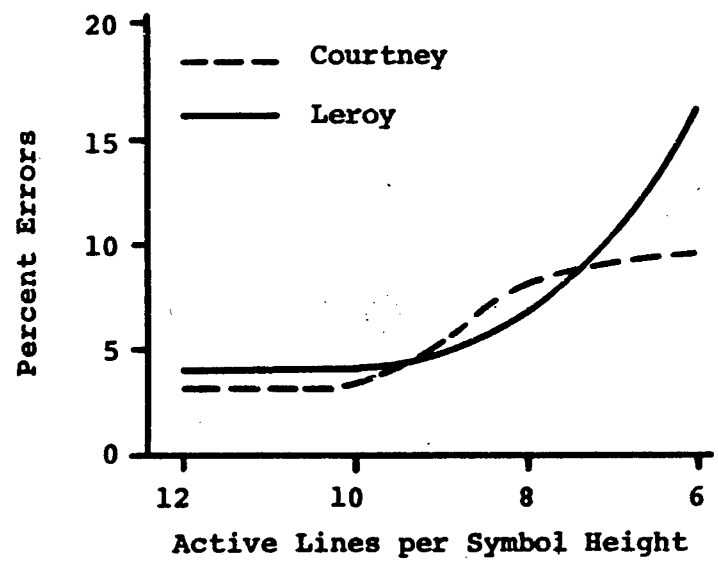


Figure 154. Identification Errors as a Function of Resolution for the Additional Practice Group, Part II. (Adapted from Ref. 306)

Elias, Sandowsky and Rizy (Ref. 114) investigated the accuracy of identification for 9 values of symbol resolution using a General Precision Laboratory Model 601 High Resolution TV with a 21 inch Conrac Model CQC Monitor. Table 69 presents the experimental variables for this study. Varying the number of active scan lines per symbol height from 3 to 11, these researchers found that accuracy of identification fell off significantly at resolutions below 5 or 6 lines per symbol height (see Figure 155). The major reduction in accuracy occurred when the symbol resolution was reduced from 5 to 4 lines per symbol height. Shurtleff (Ref. 304) comments that although these results appear to conflict with his (Shurtleff, Ref. 306), it is possible that the differences are due to the quality of the interlace which led to associated differences in the definition of a scan line. Shurtleff further states that the 5 lines used by Elias are roughly comparable to the 10 lines used in his own research and this would, therefore, approximately equate the results for both studies.

The following year Elias (Ref. 113) again studied vertical resolution using a General Precision Laboratories Model 601 High Resolution T.V. Camera and a 21 inch Conrac Model CQC Monitor with a 20 mc bandwidth and a 2:1 interlace utilizing 875 scan lines. For a complete description of the experimental variables see Table 70. Elias found that for vertical resolutions of 5 through 11 active scan lines per symbol height, performance as measured by speed of identification (error scores were negligible) significantly decreased with each increase in vertical resolution (see Figure 156). He further compared the CRT alphanumerics with non-televised printed alphanumerics under similar conditions and discovered as an examination of Figure 156 indicates, that performance at even the finest level of CRT resolution did not equal the performance obtained for the solid symbols. This author concluded that 11 active scan lines per symbol height approaches an optimal level of resolution.

Bell (Ref. 25) compared Long Gothic with Murray alphanumerics at 12, 10, 8, and 6 active scan lines per symbol height. See Table 71 for the experimental details of this study. Mean response times (see Table 72) indicate that performance systematically improved from 6 through 12 active scan lines for both fonts. This is consistent with the findings of previously cited Elias (Ref. 113) study. For accuracy of identification (see Table 73), however, only small differences in error scores were established between the 10 and 12 line conditions. Error scores substantially increased from the 10 to the 8 and 6 active scan line conditions.

The above analysis is presented as trend information since a statistical analysis was not feasible due to the limited number of subjects used and a large intra-subject variance.

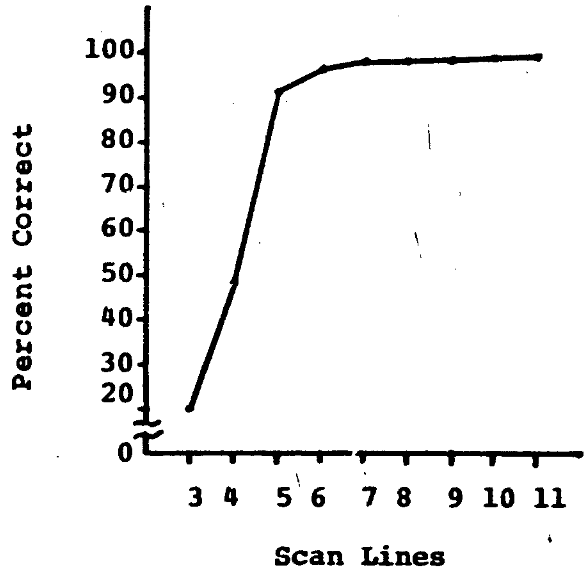


Figure 155. Mean Percent Correct Symbol Identification, Averaged Over all 36 Symbols, for Group 2 (Viewed Slides in Increasing Order of Difficulty) at Each of the 9 Levels of Symbol Resolution. (Adapted from Ref. 114)

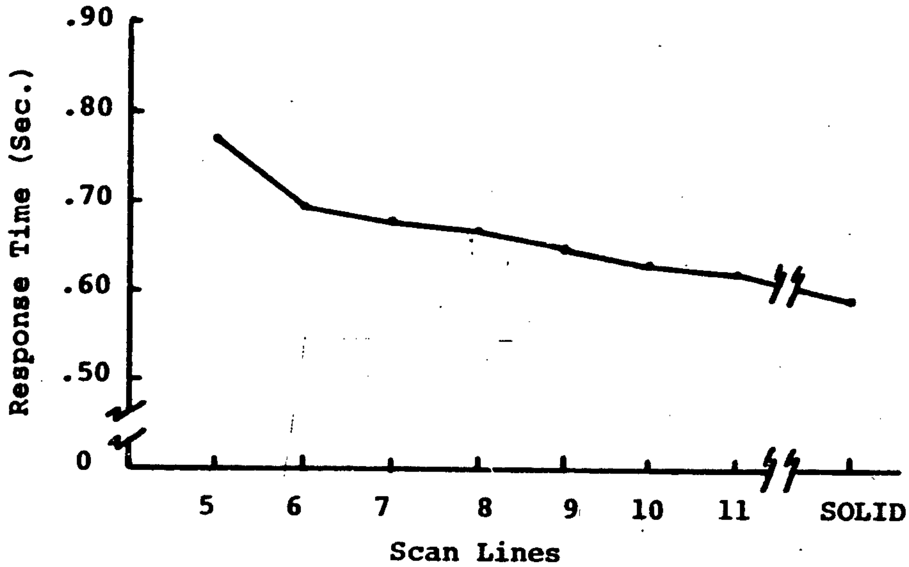


Figure 156. Mean Correct Response Time for the Average Televised Symbol at Each Level of Resolution and for the Solid-Symbol Condition. (Adapted from Ref. 113)

Table 69. Experimental Conditions for the Elias, Sandowsky and Rizy Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 10	Horizontal Spacing:
Visual Characteristics of Subjects: Uncorrected and corrected 20/20 near and far vision	Symbol-Background Relation: Light/Dark Symbol Brightness: 7.3 Ft. Lamberts Background Brightness: 1 Ft. Lambert
Number of Symbols: 26 letters 10 numbers	Brightness Contrast: 630 percent
Symbol Exposure Time: 4 seconds	Ambient Illumination: Not specified
Symbol Font or Style: Gothic/Veritype	Symbol Visual Size: 24 minutes of arc
Symbol Width/Height: Not specified	Viewing Distance: Varied to maintain constant visual size.
Symbol Stroke Width/Height: 17 percent	Viewing Angle: Zero degrees

Table 70. Experimental Conditions for Elias Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 20	Horizontal Spacing: .
Visual Characteristics of Subjects: Correct and uncorrected 20/20 near and far vision.	Symbol-Background Relation: Light/Gray
	Symbol Brightness: 7.5 Ft. Lamberts
	Background Brightness: 1 Ft. Lambert
Number of Symbols: 26 numbers 10 letters	Brightness Contrast: 650 percent
Symbol Exposure Time: Response time to identification.	Ambient Illumination: Not specified
Symbol Font or Style: Not specified.	Symbol Visual Size: 24 minutes of arc
Symbol Width/Height: Not specified.	Viewing Distance: Varied to maintain constant visual size.
Symbol Stroke Width/Height: Not specified.	Viewing Angle: Zero degrees.

Table 71. Experimental Conditions for the Bell Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 3	Horizontal Spacing: Not relevant.
Visual Characteristics of Subjects: Normal on a Bausch and Lamb Orthorater.	Symbol-Background Relation: Light/Dark
	Symbol Brightness: 60 Ft. Lamberts
	Background Brightness: 3 Ft. Lamberts
Number of Symbols: 24 letters (No J or O) 10 numbers	Brightness Contrast: 1900 Percent
Symbol Exposure Time: Latency to identification.	Ambient Illumination: Not specified.
Symbol Font or Style: Long Gothic vs. Murray	Symbol Visual Size: 16 minutes of arc
Symbol Width/Height:	Viewing Distance: Varied to maintain visual size.
Symbol Stroke Width/Height:	Viewing Angle: Zero degrees

Table 72. Mean Response Times (in seconds) for 190 Symbols Shown at Four Television Resolutions to Three Subjects. (Adapted from Ref. 113)

	Long Gothic Font TV Resolution (Number of Active Lines Per Symbol Height)			
Subjects	6	8	10	12
S_1	3.70	1.19	0.79	0.59
S_2	1.70	1.37	0.85	0.54
S_3	1.89	0.96	0.76	0.63
Mean	2.42	1.17	.80	.59

	Murray Gothic TV Resolution (Number of Active Lines Per Symbol Height)			
Subjects	6	8	10	12
S_1	3.21	1.44	0.69	0.57
S_2	2.19	1.15	0.70	0.46
S_3	1.82	0.93	0.61	0.56
Mean	2.41	1.17	.67	.53

Table 73. Number of Errors for 190 Symbols Shown at Four Television Resolutions to Three Subjects. (Adapted from Ref. 113)

Long Gothic Font

Subjects	TV Resolution (Number of Active Lines Per Symbol Height) 6	8	10	12
S_1	95	21	13	4
S_2	115	20	2	6
S_3	41	8	4	2
Mean	83.7	16.3	6.3	4.0

Murray Font

Subjects	TV Resolution (Number of Active Lines Per Symbol Height) 6	8	10	12
S_1	115	29	3	4
S_2	132	19	3	2
S_3	52	8	2	
Mean	99.7	18.7	2.7	3.0

Shurtleff, Marsetta and Showman (Ref. 305) studied CRT resolution at 10, 8 and 6 active scan lines per symbol height for two fonts. See Table 74 for study details. These researchers found that for accuracy of identification, 6 active lines per symbol height was significantly (.01 level of confidence) poorer in performance than both the 8 and 10 line conditions, but that 8 and 10 lines did not differ significantly from each other (see Table 75). Rate of symbol identification was not significantly different for any of the resolutions tested (see Table 76).

Simulated CRT studies of symbol resolution have obtained results similar to live television studies. Botha and Shurtleff (Ref. 36) studied idealized television line constructions by superimposing photographic grids made up of alternately transparent and opaque lines on solid-stroke symbols. While the exposure times used in this test were extremely short for systems application, the studies indicated that the minimally acceptable symbol resolution was between 5 and 11 lines per symbol height.

Conclusion

It is the general conclusion of this section that CRT alphanumerics require a minimum resolution of 10 active scan lines per symbol height. Any system requiring fewer action lines should be empirically tested to verify that legibility performance will not be negatively affected.

Geometrical and Pictorial Symbols

The identification of geometric or pictorial symbols on a CRT type display presents more stringent resolution requirements than are found with the different alphanumeric symbols or words. Additionally, resolution requirements for geometric symbols increase as a function of the detail of the symbol, increasing exponentially with complex figures (i.e., the identification of different aircraft by their shapes). Military type targets viewed against natural backgrounds (as opposed to a 'clear' or unnatural background) require even more resolution to optimize identification. Unfortunately, little in the way of experimental work has been done in this area.

Erickson and Main (Ref. 117) conducted one of the few studies in this area and examined the probability of correctly identifying televised military type targets as a function of the number of raster lines (and/or the minimum visual angle subtended). The targets were televised photographs of radar vans, artillery pieces, jeeps, trucks, tanks and troop carriers. Background foliage was present in all of the photographs. Eight subjects viewed the ten inch, 525 line raster scanned CRT tube

Table 74. Experimental Conditions for the Shurtleff, Marsetta and Showman Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 24	Horizontal Spacing: 25 percent
Visual Characteristics of Subjects: 20/20 near and far acuity; normal phoria and color.	Symbol-Background Relation: Light/Dark
	Symbol Brightness: 20 Ft. Lamberts
	Background Brightness: 2 Ft. Lamberts
Number of Symbols: 26 letters 10 numbers	Brightness Contrast: 900 percent
Symbol Exposure Time: Response time to identification.	Ambient Illumination: 6 to 8 Ft. Candles
Symbol Font or Style: Standard Leroy vs. Revised Leroy.	Symbol Visual Size: Varied with viewing distance.
Symbol Width/Height: 75 percent	Viewing Distance: Variable
Symbol Stroke Width/Height: 17 percent	Viewing Angle: Zero degrees

Table 75. Visual Angles of Subtense Required for 85 and 99 Percent Accuracy of Identification. (Adapted from Ref. 305)

Resolution in Lines Per Symbol Height	Leroy Symbols: Standard, Identification Accuracy (Percent)		Leroy Symbols: Revised, Identification Accuracy (Percent)	
	85% (Minutes of Arc)	99% (Minutes of Arc)	85% (Minutes of Arc)	99% (Minutes of Arc)
10	7.58	13.15	7.59	13.37
8	7.57	12.82	7.70	15.09
6	10.35	35.97	11.01	30.08

Table 76. Identification Rates for the 85 and 99 Percent Accuracy of Identification. (Adapted from Ref. 305)

Resolution in Lines Per Symbol Height	Leroy Symbols: Standard, Identification Accuracy (Percent)		Leroy Symbols: Revised, Identification Accuracy (Percent)	
	85% (Symbols/Sec.)	99% (Symbols/Sec.)	85% (Symbols/Sec.)	99% (Symbols/Sec.)
10	1.16	2.00	1.25	1.89
8	0.74	1.22	1.25	1.54
6	1.33	2.04	1.16	1.85

at a distance of 24 inches. Contrast was reported as 'adequate'; other luminance data were not reported. Results of this study are summarized in Figure 157.

As was found in the studies on alphanumerics, the probability of detection increases significantly when the number of raster lines is increased from 5 to 6 lines per symbol height with no significant increase thereafter. For identification, however, a more consistent increase is found as the number of lines per symbol height is increased from 5 to 17 lines. The extrapolation (by Semple and Gainer, Ref. 294) indicates that this same slope continues up to 100% probability of identification. Semple and Gainer suggest that up to 25 lines per symbol height may be required to optimize identification performance. Further research is recommended for the higher resolution values as a number of other parameters (effects of symbol width to height on recognition, strokewidth to height - if applicable, increasing symbol area) are not accounted for in the study examined here.

Semple and Gainer (Ref. 294) report the results of a study conducted by Marsetta and Shurtleff (Ref. 390) which studied the probability of correctly identifying military map symbols against a natural background. A 945 line display screen was used in this study, with the number of raster lines being varied by changing the symbol height.

The results of the study are presented in Figure 158. It is observed that a rapid increase in the probability of correct identification occurs between 9 and 14 lines per symbol height and that an insignificant increase results thereafter. Although this appears to be contradictory to the results found by Erickson and Main (Ref. 117), these differences may possibly be accounted for by differences in methodology, symbology type, clutter and equipment used.

Johnson (Ref. 184) conducted a study to determine the effects of horizontal resolution and shades of gray on target recognition. Twelve visually screened subjects viewed a Conroc Model CNB8 TV Monitor with a 10 megacycle bandwidth used as a simulated cockpit display from a fixed distance (head in chin-rest) of 24 inches. Three resolution levels were used (200, 400, and 550 lines per display height) together with three shades of gray (5, 7, and 9). Terrain and display luminance levels were maintained at 100 ft L with a white frame constructed around the display tube to provide the 12 coordinate cells for the observer. The movable terrain model was adjustable to simulate a 30 degree dive angle from 6,000, 9,000, and 12,000 feet with a maximum terrain exposure time of 10 seconds. The target models (750:1 scale) were scale models of three military vehicles (2-1/2 ton truck, 5 ton cargo truck, and a tank with a 90 mm gun mounted on it) and the calculated angular subtense of the length and height of the targets at 6,000, 9,000 and 12,000 feet, and 15,000 feet were 20 x 13, 13 x 9, 10 x 7, and 8 x 5 minutes of arc respectively.

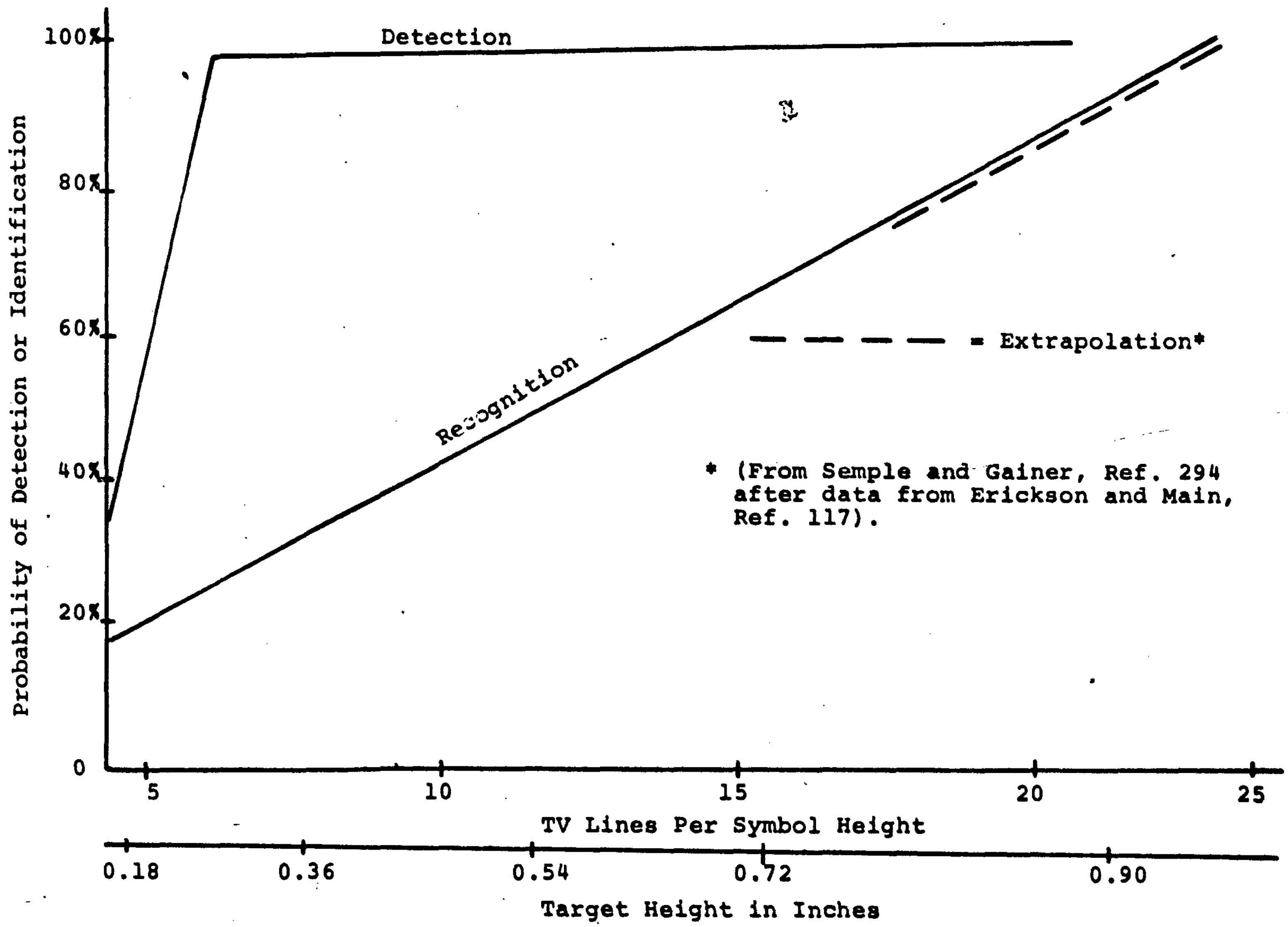


Figure 157. Probability of Detection and Recognition as a Function of Number of Active Scan Lines. (After Erickson and Main, Ref. 117)

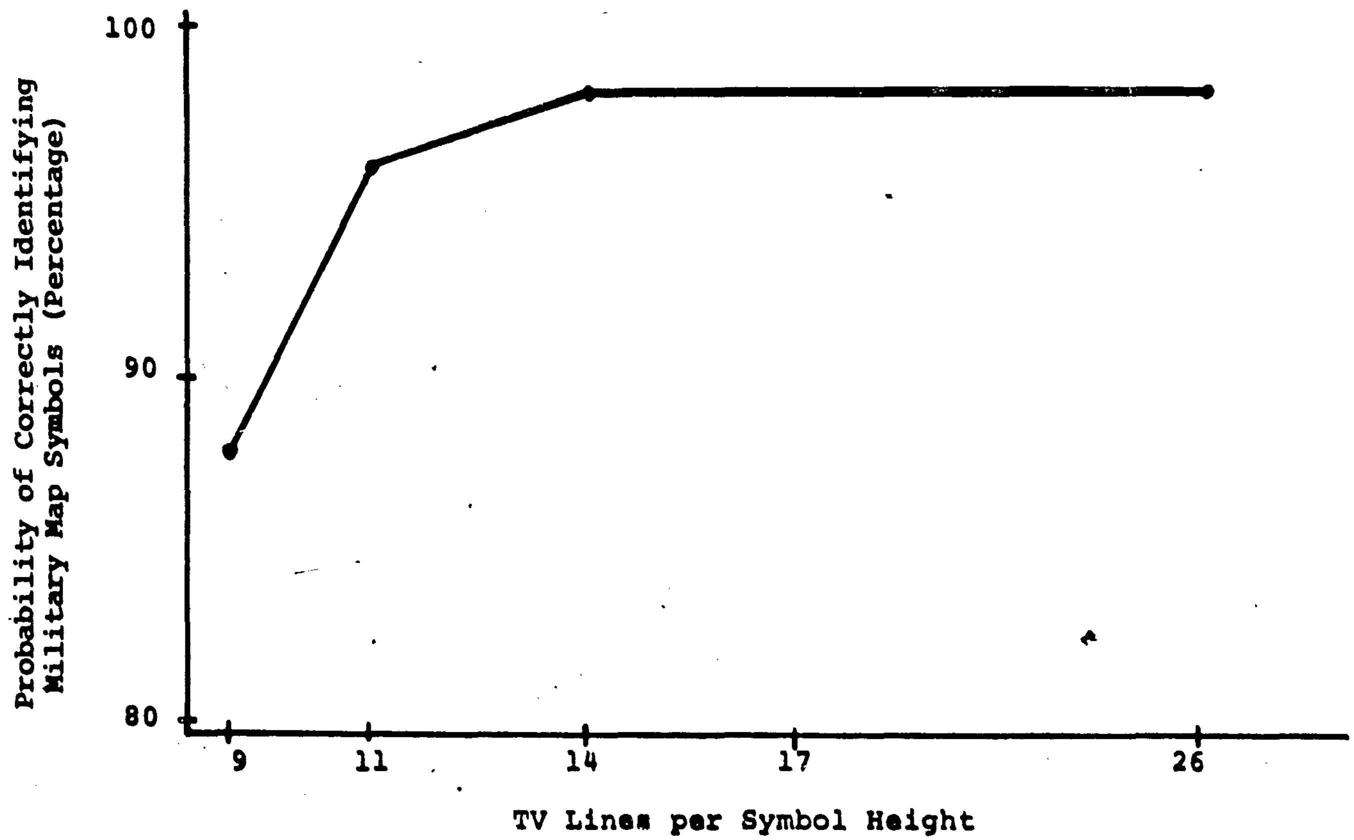


Figure 158. Probability of Correctly Identifying Military Map Symbols as a Function of the Number of TV Lines per Symbol Height. (After Ref. 294)

The observers task was to find the target (at which time he released a thumb button to stop the timer) and then to specify the location of the target using the grid coordinates.

The results of the study are summarized in Figure 159a and Figure 159b. Johnson concluded that the horizontal resolution had a highly significant overall effect on target recognition. Reliable differences were found between 200 and 400 TV lines at 12,000 and 15,000 feet and between 200 and 550 TV lines at every altitude. An apparent inverse relationship was found between target recognition time and horizontal resolution (and shades of gray). Because target size and number of scan lines through the target have a linear relationship with slant range, these two factors may largely account for the reliable effect of slant range on target detection.

Hemingway and Erickson (Ref. 163) conducted an experiment to clarify the relative effects of image size and the number of raster lines per image upon observer performance. Eight visually screened subjects viewed an eight inch Conroc Model RNC9-A with 525 active scan lines, 2:1 positive interlace and a 10 megacycle bandwidth. Sixteen symbols (from the 20 recommended by Bowen, Andressi, Traux, and Orlanski, Ref. 38) were used in the test (Figure 160). Each test chart contained 25 symbols (one each of the original 16 and 9 randomly chosen from the 16) randomly located, but with constant orientation. The symbol images on the monitor were made up of 4.8, 6.3, 7.8, 13.5, 15.5, and 25.6 raster lines per symbol height while the angular subtense of each symbol was varied from 4.4', 6.0', to 10.2' of arc (by varying the observer-to-monitor viewing distance). The observer task consisted of verbal identification of each of the 25 symbols on the card, but only the first identification of each type of symbol was counted.

The mean scores as a function of the symbol angular subtense and the number of active scan lines per symbol height are presented in Figure 161a and Figure 161b respectively. It is observed from these figures that at all angular subtenses and at values above 7.8 lines per symbol, performance improved as the number of lines per symbol increased. (Below 7.8 lines per symbol, performance appeared to be random). The data in Figure 161b indicates that performance does not improve as the angular subtense of the symbol increases when there are only 4.8 or 6.3 scan lines per symbol. However, there is a definite improvement with increased angular size of symbols made up of 7.8 scan lines or more per symbol.

Hemingway and Erickson (Ref. 163) discuss the results of an earlier experiment conducted by Baker and Nicholson (Ref. 14) in which a flying spot scanner was used to generate raster lines making up alphanumeric symbols (total of 20 used) consisting of 8, 10, 12, 16, and 20 active scan lines per inch of display. Resolution, size, height-to-width ratio, symbol orientation and

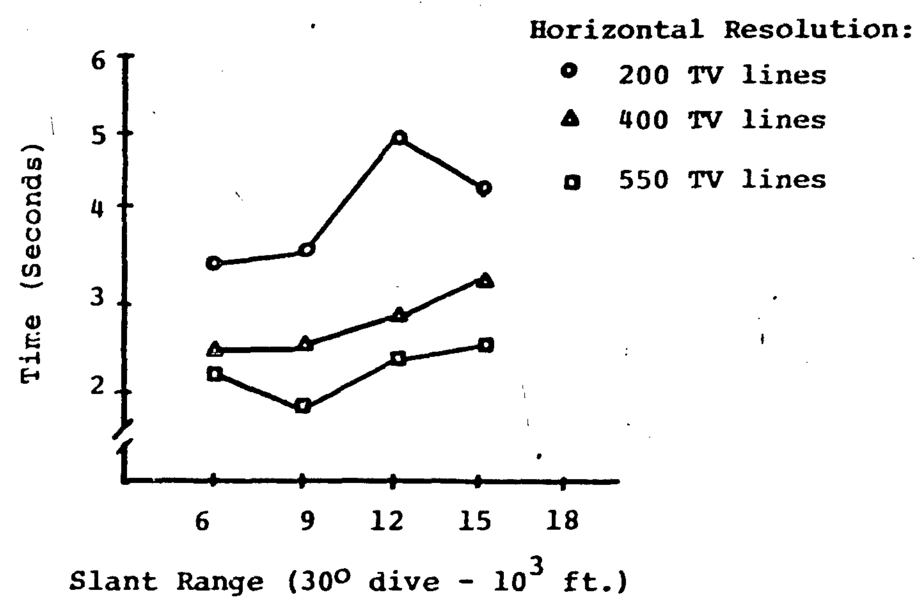


Figure 159a. Target Recognition Time as a Function of Horizontal Resolution. (Johnson, Ref. 184)

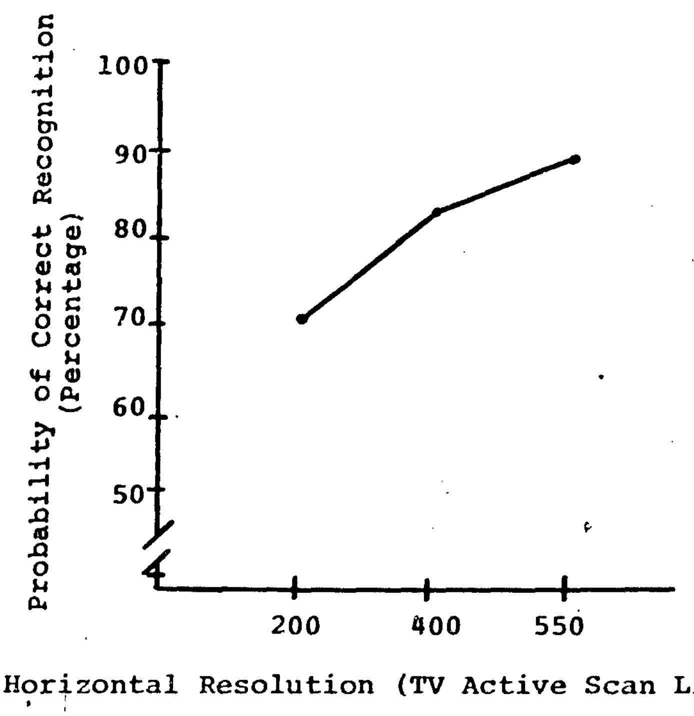


Figure 159b. Probability of Correct Recognition as a Function of Horizontal Resolution. (Adapted from Johnson, Ref. 184)

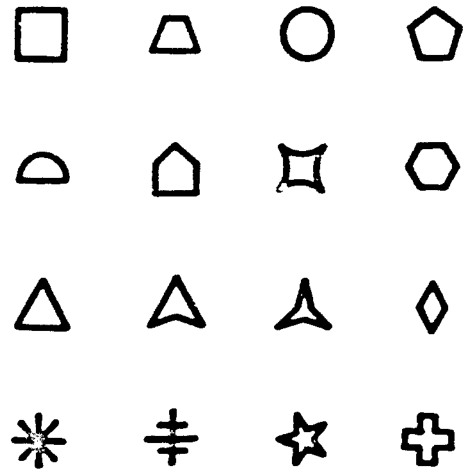
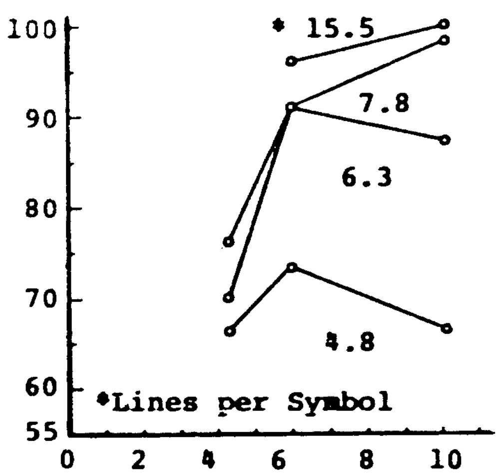
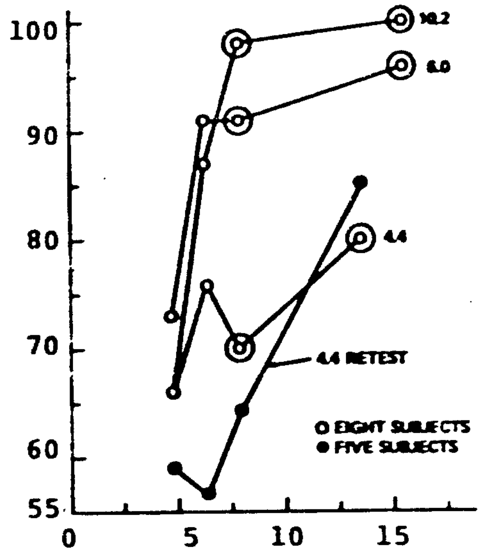


Figure 160. Geometric Figures Used by Hemingway and Erickson. (Ref. 163)



b. Percentage Correct Response as a Function of Angular Subtense (Min of Arc) for Four Different Number of Scan Lines Per Symbol.



a. Correct Response as a Function of Number of Lines Per Symbol.

Figure 161. Percentage Correct Response as a Function of (a) Angular Subtense and (b) Scan Lines Per Symbol Height.

viewing distance were controlled variables. Three symbol heights were used (0.353, 0.418, and 0.448 inch which is equivalent to 10', 15' and 20' of arc). Results of the Baker and Nicholson study indicated that identification of the symbols deteriorated rapidly below 15 minutes of arc at the higher resolutions (16 and 20 lines per inch). At eight lines per inch, the deterioration began at 20 minutes of arc. Better performance was obtained at 16 lines per inch than at 8, 10 or 12 lines at all angular subtenses.

Only three studies have been found in the literature that have separated the main effects of visual subtense and the number of active scan lines (Shurtleff et al., Ref. 305; Baker and Nicholson, Ref. 14; and Hemingway and Erickson, Ref. 163). Of these three, only the study by Baker and Nicholson and the study by Hemingway and Erickson are similar enough in methodology and objectives to be comparable. Even these two studies have a number of differences that need to be accounted for, but the data from these studies are sufficiently in agreement to allow the prediction of several interesting trends. Some of the differences were:

1. Baker and Nicholson used 20 alphanumeric symbols randomly oriented on the display, while Hemingway and Erickson used 16 geometric forms with a constant orientation (the alphanumerics had reduced probability of being correct by chance).

2. The performance level obtained in the Baker and Nicholson study was not as high as the performance obtained in the Hemingway and Erickson study.

Figure 162 is a replot of the data from the above two studies with the three symbol heights used by Baker and Nicholson (0.353, 0.418, and 0.448 inch having been assumed to have a mean height of 0.4 inch (10 minutes of arc). It is observed that the data are in relatively close agreement.

Hemingway and Erickson (Ref. 163) compared the data from the study by Shurtleff et al. (Ref. 305) and from Baker and Nicholson (Ref. 14) at various levels of subject error. The data used were taken from Figure 5 in the Baker and Nicholson study and from Figure 2 in Shurtleff's report. The replotted combined data are presented in Figure 163 a, b, c, and d. It is interesting to observe that the figures suggest a tradeoff between lines per symbol height and the visual angle subtended by the symbols. It appears that as the number of lines per symbol height decreases, the same or equivalent performance level may be maintained by increasing the angular subtense of the symbol. This tradeoff holds for symbols with visual angles between 7.8 to 16 minutes of arc. There appears to be a asymptote at or about 16 minutes of arc. Apparently,

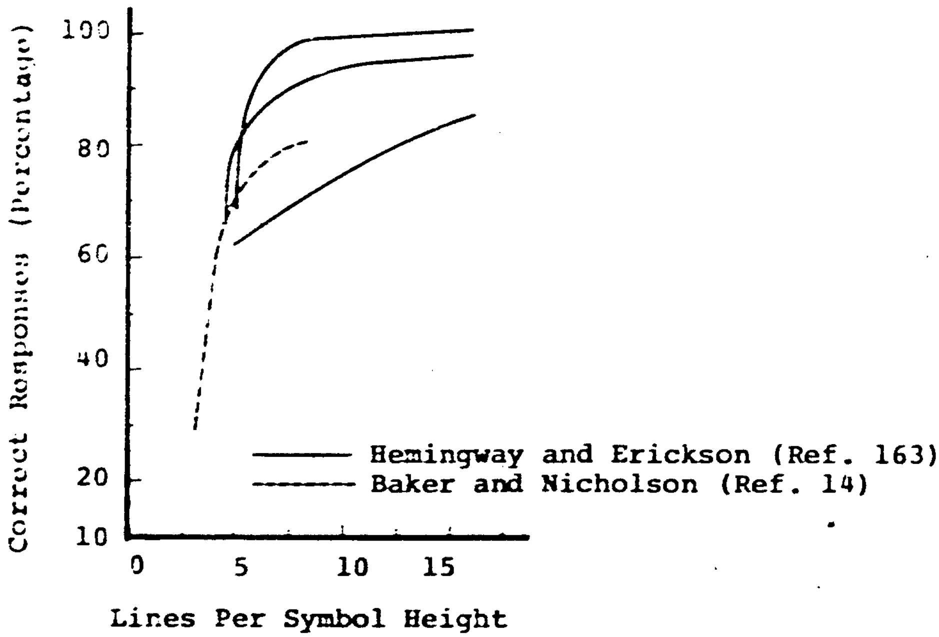


Figure 162. Comparison of Smoothed Data from Baker and Nicholson (Ref. 14) and Hemingway and Erickson (Ref. 163). (Adapted from Ref. 163)

further decreases in the number of active scan lines cannot be balanced by increases in angular subtenses above 16 minutes of arc.

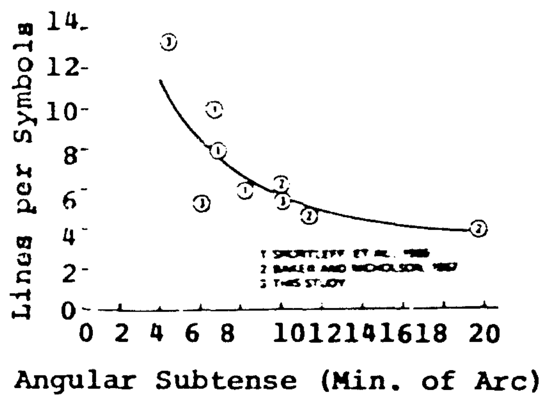
Conclusions

The literature indicates that, in general, geometrical or pictorial symbols require 33% to 100% more resolution (number of active scan lines per symbol height) than do alphanumeric symbols on the same display for 100% correct identification. However, some tradeoff is possible between the number of active scan lines and the visual angle subtended by the symbol. In general:

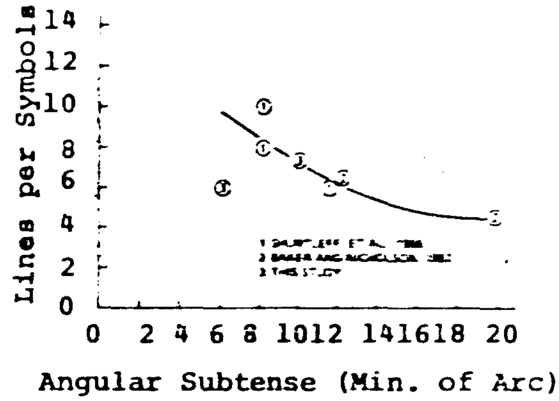
1. A minimum of 16 lines per symbol height is required for 90% plus probability of correct identification.

2. Performance level improves as the number of scan lines per symbol height is increased (but this factor is interactive with the angular subtense of the symbol).

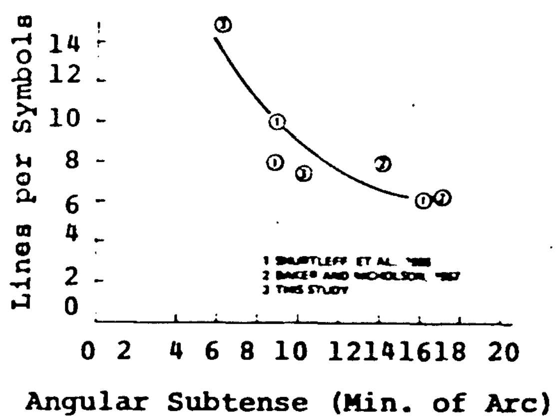
3. Performance improves as the angular subtense of the symbol is increased (up to an apparent asymptote at the 16 minutes of arc).



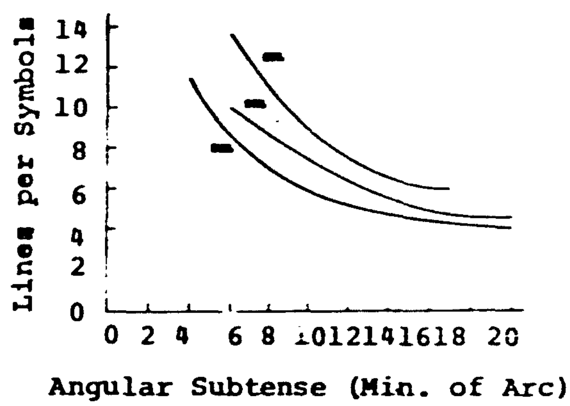
a. Requirements for 80% Correct Response



b. Requirements for 90% Correct Response



c. Requirements for 95% Correct Response



d. Requirements for 80, 90, and 95% Levels of Correct Response

Figure 163. The Number of Scan Lines and the Angular Subtense Requirements for 80% (a), 90% (b) and 95% (c) Levels of Correct Responses. (Adapted from Hemingway and Erickson, Ref. 163)

4. For targets with visual angles between 8 minutes and 16 minutes, the same performance level may be maintained as the number of scan lines is decreased by increasing the visual angle of the symbol (up an asymptote at 16 minutes). Above 16 minutes, this inverse relationship does not appear to hold.

QUALITY OF EQUIPMENT

Quality of equipment refers to comparisons between 525 and 945 line raster TV systems. When the number of active scan lines per symbol height and the visual angle of subtense for given symbology are held constant, then the remaining equipment factors (including bandwidth, beam, focusing, etc.) influencing symbol legibility are loosely grouped and called "quality" features of the two raster TV systems.

Shurtleff and Owen (Ref. 307) examined the legibility of alphanumerics displayed on two television systems incorporating different raster resolutions. The two televisions compared were fundamentally 525 and 945 line raster systems. For a more detailed description of these see Table 77. Alphanumerics were viewed at individual resolutions of 6, 8, 10 and 12 active scan lines per symbol height for each of the TV systems. The experimental conditions surrounding this comparison are presented in Table 78.

For speed of symbol identification no significant difference was found between either the 525 or 945 line television system at any of the individual resolutions tested (see Figure 164). For accuracy of identification, the 12, 10, and 8 line resolutions were similar for both the 525 and 945 line systems, but the 6 lines per symbol height was significantly poorer for the 525 line system (see Figure 165). Error rates, however, were unacceptable for systems usage for both the 525 and 945 line systems at the 6 line per symbol height resolution. Both TV systems required a minimum of 10 active scan lines per symbol height before error rates dropped to an acceptable usage level. Because no significant difference existed for either the 525 or 945 line system at the usable 10 or 12 line resolutions, it would seem that for systems application there is no apparent advantage in using the higher resolution system.

Conclusion

Research findings indicate there is no apparent alphanumeric legibility difference in the use of either the 525 or 945-line raster TV for usage.

Table 77. Specifications for 525 and 945 line Raster Television Systems. (Adapted from Ref. 307)

Specification	525 line	945 line
Input Power	50/60 Cycles, 95-125 vac., 0.5 amp., 45 watts	115 vac., 50-60 cps., control voltage
Scanning	Horizontal frequency 15750 HZ; crystal controlled; vertical	Horizontal frequency 28,350 HZ; vertical frequency, 60 HZ.
Frame Rate	30 HZ; 2:1 interlace	30 HZ; 2:1 interlace
Resolution	Horizontal, 400 lines; vertical 300 lines, apparent	1,000 lines (center) at 675, 875 and 945 lines/frame, vertical 600 lines
Bandwidth	Nominal, 5Mc	17Mc ± 1.0 db
Output	Composite video, 1.5 v. into 75 ohm line; RF:100 mv.; channels 2-6 into 75 ohm line.	Video, 1.0 v. non-composite, 1.4 v.; composite impedance, 75 ohms, 2 outputs
Operating Control	Beam, target, electrical and optical focusing, aperture control	Beam target, pedestal, gain electrical and optical, focusing, aperture control

Table 78. Experimental Conditions for the Shurtleff and Owen Study.

EXPERIMENTAL CONDITIONS	
Number of Subjects: 4	Horizontal Spacing: Not relevant
Visual Characteristics of Subjects: Normal Vision Bausch and Lamb Orthorater	Symbol-Background Relation: Light/Dark
	Symbol Brightness: 20 Ft. Lamberts
	Background Brightness: 2 Ft. Lamberts
Number of Symbols: 26 letters 10 numerals	Brightness Contrast: 900 percent
Symbol Exposure Time: Response time to identification.	Ambient Illumination: Not given.
Symbol Font or Style: Leroy	Symbol Visual Size: 11 minutes of arc
Symbol Width/Height: 75 percent	Viewing Distance: Varied to maintain symbol size.
Symbol Stroke Width/Height: 17 percent	Viewing Angle: Zero degrees

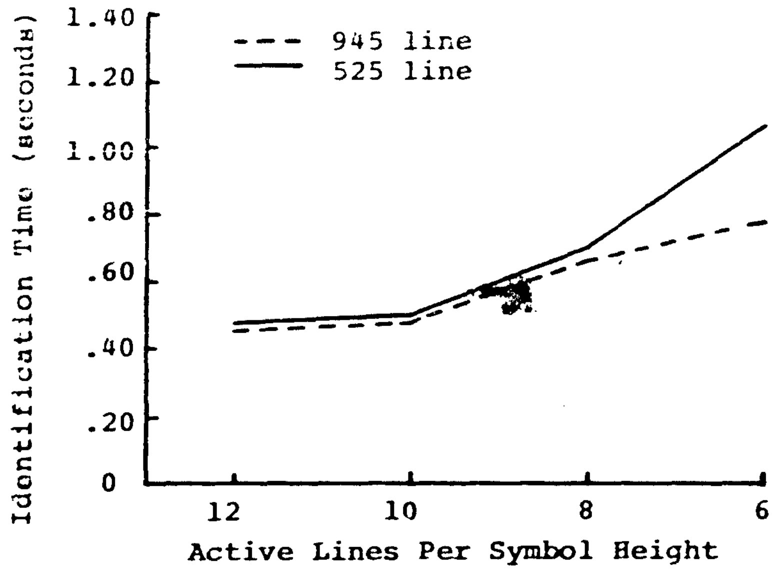


Figure 164. Average Symbol Identification Times.
(Adapted from Ref. 307)

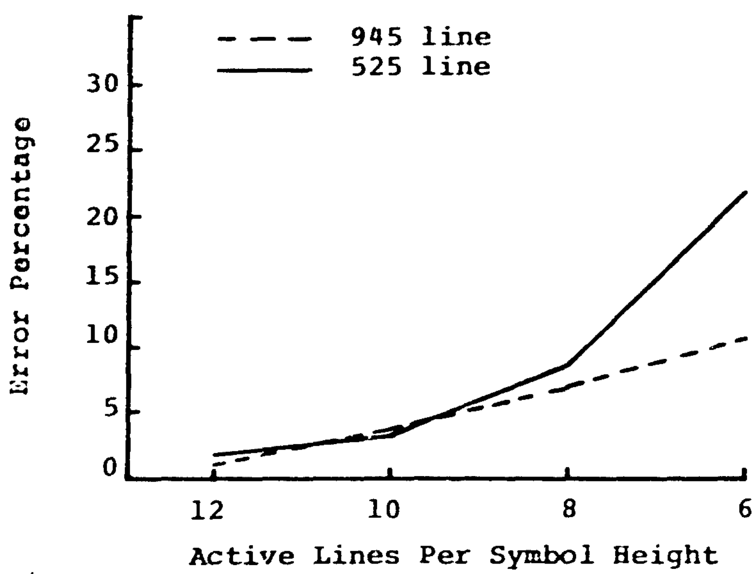


Figure 165. Average Error Percentage.
(Adapted from Ref. 307)

VIDEO BANDWIDTH

Few data are available showing the relationship between video bandwidth and the resolution (legibility) of symbology. Shurtleff (Ref. 304) reports the findings of an unpublished study by Seibert in which ninety subjects viewed alphanumerics on TV monitors from a variety of positions and with five bandwidths: 4.0 mc, 2.0 mc, 1.5 mc, and 750 kc. The results indicated a complex relationship between bandwidth, vertical symbol resolution and visual angle of the symbol. Generally, there was little difference between 4 and 2 mc at any value of symbol resolution. Decreasing the bandwidth below 2 mc, however, progressively decreased identification accuracy. The average overall performance is shown in Table 79.

The data failed to show if symbol identification accuracy is affected by video bandwidths above 4 mc. Many of the "high-resolution" displays have bandwidths as high as 20 mc. They do indicate that for practical operations, bandwidths below 2 mc should not be used, but even this value should be accepted with caution, for few of the experimental conditions (such as the various brightness levels) were specified for this study. Additionally, Shurtleff indicated that the subjects were not visually screened for the experiment.

Shanahan (Ref. 300) conducted a study to examine the effects of bandwidth reduction on the correct identification of acuity targets. Thirteen-sixteenth inch Landolt rings were mounted on a 4 x 8 foot aerial photograph (taken at 35,000 ft.) and viewed by a TV camera mounted 11 feet away. Bandwidths of 8.0 mc, 2.0 mc and 1.0 mc were used with a Conroc 8" monitor (Model CNA8) to present the Landolt rings to the six subjects (viewing distance from observer to the display screen was not specified). Size of the rings was varied through the use of a zoom lens mounted on the TV camera. Contrasts of 100%, 81% and 27% were used between the rings and the background while the gap in the ring (1/32 inch) was presented in four different orientations. The subjects were instructed to report the orientation of the ring gap when it became visible. The time to respond was the performance measurement used.

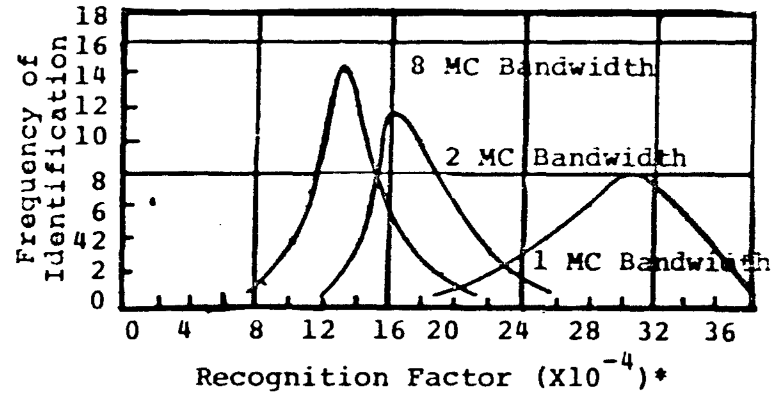
A summary of the results are presented in Table 80. Reducing the video signal bandwidth from 8.0 megacycles to 2.0 megacycles degraded the ability of the test subject to identify the target by a mean value of 23% for the 100% contrast level, 24% for the 81% contrast and 15% for the 27% contrast level (Figure 166). Reducing the bandwidth from 8.0 to 1.0 megacycle degraded the observer's ability to identify the target by mean values of 54%, 52% and 42%, respectively. Shanahan concludes that the ability to correctly identify targets is degraded less by video bandwidth reductions for low contrast targets than for high contrast targets (but it starts degrading from a poorer performance level). Likewise, the ability to identify targets is degraded less by target

Table 79. Summary of Results in Experiment by Shurtleff. (Ref. 304)

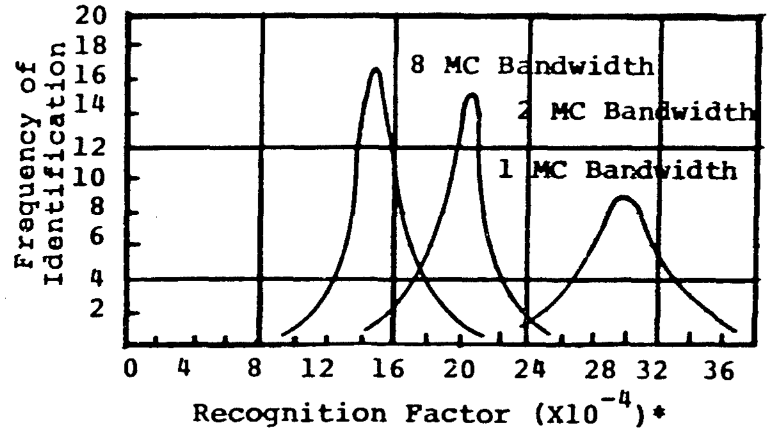
Lines Per Symbol Height	Vertical Visual Size Min Arc	Horizontal resolution in Bandwidth 4.0 MC	2.0 MC	1.5 MC	1.0 MC	750 KC
18	15	99.8% Correct response	99.8%	99.1%	99.3%	92.1%
	10	95.1	95.7	97.3	97.0	84.1
	7	95.1	94.4	98.1	81.5	60.1
14	12	98.8	98.9	97.5	97.2	[illegible]3.4
	8	85.8	91.0	88.7	86.8	68.6
	6	83.0	83.4	90.2	62.4	32.5
10	9	97.0	97.2	90.5	92.6	58.8
	6	71.1	83.5	68.7	58.8	44.6
	5	56.6	68.0	63.5	34.5	13.5
6	6	75.5	57.8	36.4	33.1	18.2
	4	23.1	34.2	16.6	10.1	8.0
	3	6.6	17.0	10.1	4.9	2.0
Average - All Sizes and Distances		74.0	76.8	71.4	63.1	47.2

Table 80. The Effects of Video Signal Bandwidth and Target Contrast on Target Identification Ability.
(After Shanahan, Ref. 300)

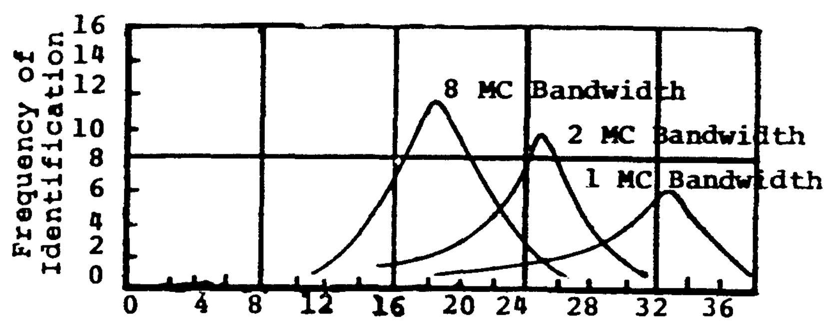
Video Signal Bandwidth (Megacycles)	Contrast Ratio Targets 100%	81%	27%	Target Contrast Ratio (Percent)	Video Signal Bandwidth (Megacycles) 8	2	1
	mean degradation				mean degradation		
8 to 2	23%	24%	15%	100 to 81	7.4%	7.9%	3.8%
8 to 1	54%	52%	42%	100 to 27	26 %	18 %	6.6%



a. Frequency Distribution Using 100% Contrast Landolt Rings.



b. Frequency Distribution Using 81% Contrast Landolt Rings.



*Recognition Factor (X10^{-4}) = $\dfrac{\text{Displayed Target Width}}{\text{Width of Visual Background}}$

c. Frequency Distribution Using 27% Contrast Landolt Rings.

Figure 166. Results of the Study by Shanahan Using 100% (a), 81% (b), and 27% (c) Contrast Between Target and Background. (After Ref. 300)

contrast reduction when using a narrow bandwidth than when using a wide video bandwidth (but again starting from lower performance levels). Shanahan, however, warns against over-generalization of these conclusions.

General Conclusions

From the existing data the following general conclusions are drawn:

1. Resolution requirement (number of active scan lines) varies as a function of the type of symbol used and as a function of the background against which it is to be viewed (Table 81).

2. The number of active scan lines required for detection is considerably less than for the same probability of identification.

3. Fewer scan lines are required for alphanumeric symbols than for geometric or pictorial symbols.

4. Alphanumerics require 10 to 12 lines per symbol height for a reasonably high probability of correct identification.

5. Sixteen to twenty lines per symbol height are required for the same degree of correct identification of geometric-pictorial symbols.

6. A minimum of eight lines per symbol height is required for a reasonable probability of detection of geometric symbols (80% plus).

7. A minimum of 1.7 to 2 megacycles of bandwidth are required for the above values.

8. The number of lines per display height did not appear to be a significant factor in the probability of detection. The standard 525 lines appears to be adequate (under normal viewing conditions).

9. Some tradeoff is possible between the number of scan lines per symbol and the angular subtense of the symbol.

Table 81. Summary of Recommended Number of Lines per Symbol Height.

	ALPHANUMERIC	GEOMETRICAL-PICTORIAL
Detection:	8-10 lines per symbol height	8-10 lines per symbol height
Identification:	10-12 l. .es	18-20 lines

IMAGE QUALITY

The information extracted from a display or an image depends largely upon the quality of the image. All images, be they photographic, TV, RADAR or infra-red, are subject to a myriad of degrading factors depending upon the course of its acquisition and display (degradation arises from such factors as the undulatory nature of radiation, atmospheric turbulence, haze, limited system resolution, system bandwidth, dynamic range, system noise, edge-gradients, display jitter, image smear and display grain size). These factors generally act to increase the homogeneity of the image spatial-luminance distribution. That is, instead of being sharply separated, adjacent luminance areas in the image are connected by diffused spatial-luminance transitions. Hence, contrast is reduced and image elements which would be otherwise resolvable, become indistinguishable and the information transmission capability is thus reduced. This section will briefly address the factors of edge gradients, display jitter, image smear, and display grain-size and their effects on resolution.

Edge Gradients

Resolution has traditionally been regarded as an index of image quality, but it merely designates the minimum detail that can be resolved and, as such, provided no information as to the clarity and sharpness of the larger details in the image. Brainard (Ref. 41) suggests that: "From a study of resolution and detail contrast characteristics of photographic and television images it has been long apparent that the sharpness of an image has no fixed relation to the limit of resolution of the system". Sharpness is rather a function of the shape and steepness of the edge gradient of the image. Higgins and Jones (Ref. 166) investigated edge gradients measurements and found that a number of the commonly accepted methods to be unsatisfactory. One index investigated was the maximum gradient, which usually occurs near the center of the curve. As a measure of sharpness, this index failed to distinguish an edge gradient having a sweeping toe and

shoulder from one with an abrupt toe and shoulder (Figure 167). An index based on the average gradient (e.g., point A and B in Figure 167) between two points likewise failed to distinguish between curves like E (or F) and D which have the same average gradient. The final index they examined, acutance, correlated highly ($r = 0.994$) with observer judgements of sharpness. This index is generally defined as the mean-square gradient divided by the density difference, or:

$$6_x^{-2} = \Sigma \frac{(\Delta Di/\Delta xi)^2}{n} / DS$$

where n is the number of measurements and DS is the density difference between points A and B. Further research by Higgins and Jones indicates that a more satisfactory index of image 'definition' was obtained by combining resolution with acutance. They suggest the following empirical expression:

$$\text{Definition} = \text{Acutance} \cdot e^{-KR^2}$$

where K is a constant and R is resolution. The precise relationship of acutance and resolution in their joint effect on definition remains to be worked out (Ref. 41). In addition to these factors, graininess has also been found to influence sharpness. At present, image definition is believed to be influenced principally by:

sharpness (measured in terms of edge gradient)

resolution

graininess

tonal reproductions(Tona)

Of these factors, Brainard (Ref. 41) concluded that sharpness is the more important.

Edge gradients have another important role in the field of perception. When the small involuntary eye movement present in the normal viewing conditions are prevented from producing motion of the retinal image, the whole visual field appears uniform, in spite of actual luminance variations across the field. Brainard (Ref. 41) quotes Riggs (Ref. 276) as saying that "Continuous involuntary motion of the eye has one clearly demonstrated function, that of preventing the ... disappearance of contours..".

The efficiency with which a display is searched is significantly impaired when the edge gradation is reduced by blurring the image or by introducing differently shaped apertures. Specifically, the duration of fixation increase and the distances between fixations decreases, as the edge gradients are diffused. The net result of this is that a smaller portion of the display is searched in the given unit of time. The magnitude of this effect is illustrated in Figure 168.

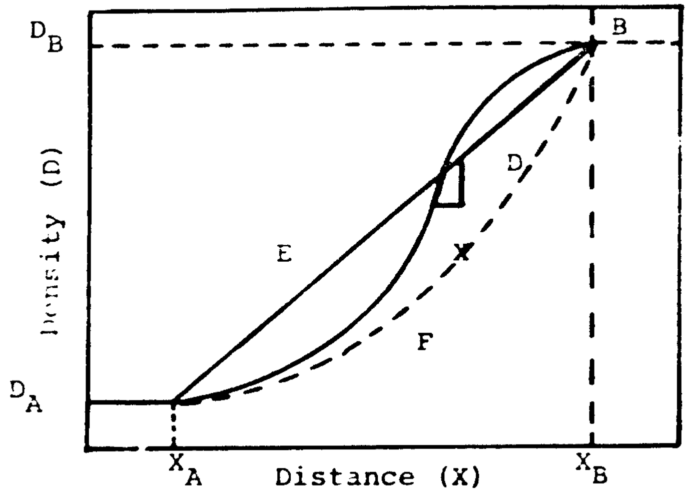


Figure 167. Distribution of Density in Image of Knife-Edge. (Brainard et al. Ref. 42)

Brainard et al. also suggests that in addition to search time, the identificability of targets will be significantly reduced and target detection will be affected but to a lesser degree.

The optical characterisiics of the eye are such that the image projected unto the retina is degraded relative to the image entering the eye. Regardless of how sharp the edge gradient is between adjacent luminance areas, the distribution of the luminance on the retina will be spread or diffused. This spread derived from the eye is introduced by:

1. Diffusion of the light by the pupillary aperture

2. Spherical and chromatic aberration of the ocular system

3. Scatterning of light in the dioptic media

The resulting diffusion of the image has been typically regarded as the "Blur Circle" and more recently as the spread function (see section on Visual Acuity) of the visual system.

In spite of the diffusing effects of the eye, the retinal image can still be perceived as sharp under many conditions. The relationship of the actual, perceived and retinal image is shown in Figure 169. This phenomena was apparently first noticed by Mach (Ref. 228) in 1865 and he described it as a second derivative correction applied to the retinal image. The equation proposed was:

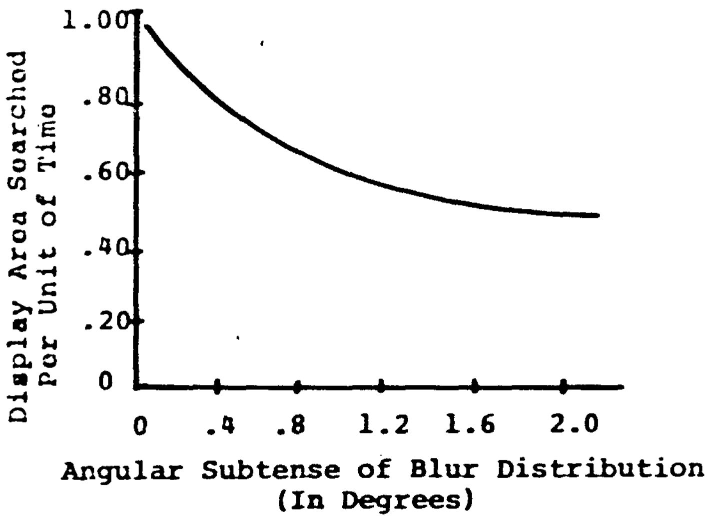


Figure 168. Influence of Edge-Gradient Diffusion on Search Efficiency. (After Brainard et al. Ref. 42)

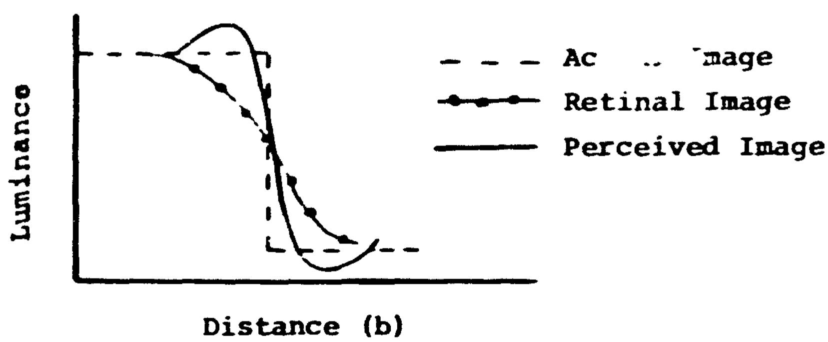


Figure 169. Perception of a Bipartite Field. (After Brainard, Ref. 41)

$$r(X) = \alpha \log \frac{e(X)}{\beta} \pm \frac{r}{e(X)} \cdot \frac{d^2 e(X)}{d_X^2}$$

where x is the axis along the surface of the retina, r is the perceived (or apparent) brightness, e is the retinal illuminance, and α, β, and r are constants. Mach noted also that the first derivatives of the spatial-luminance distribution had little or no effect on perception, a finding recently confirmed by Ludvigh (Ref. 221).

<u>Display Jitter</u>

Another factor contributing to edge gradient reduction is display jitter. Jitter is defined by Sherr (Ref. 301) as the detectable motion in displayed data, when no such motion should exist. It is essentially the noise component of a visual presentation that sets the lower limits of motion perception and consequently resolution (perception) capabilities. Jitter can be detected when the motion is of sufficient intensity to be detected by the eye at the selected viewing distance. With a line width of three minutes of arc, it is probable that a motion of between 1/2 and 1 line width will be apparent, as either blurring of the image caused by widening of the line or actual motion of the image. The nature of the distortion induced will depend upon the jitter frequency and upon whether the two lines overlap. If, for example, the jitter frequency is above critical fusion frequency for flicker and the lines do not overlap, then two images will appear. If the frequency is below CFF without line overlap, the image will appear to move from one position to the other. If the lines do overlap, they will appear to broaden at frequencies above CFF and produce additional flicker at frequencies below CFF. Sherr suggests that some jitter may be acceptable if the visual presentation requirements are not exceeded, but that in general it is desired that this type of display noise be limited to less than a resolution element to achieve acceptable performance (Table 82).

<u>Image Smear</u>

As Slocum et al. (Ref. 312) point out, many operational aircraft today have low-resolution ground mapping radar systems. These systems are employed only for the recognition of large land/water boundaries, outlines of large cities, etc., and for this task the primary factor is sufficient brightness to be recognized under all ambient light conditions. Slocum et al. suggest that a display utilizing the fading erasure technique is adequate since image grey scale and resolution are not critical. But, in order to recognize smaller targets, the ground coverage of the sensor must be smaller. This results in considerable image motion between frames at normal aircraft speeds. For example, with a three-mil radar coverage, a point

Table 82. Jitter Effects on Line Perception.
(After Sherr, Ref. 301)

Jitter Frequency	Line Motion	Line-Overlap	Line not Overlapped
Above CFF	1/2 to 1 line width	Lines broaden and "blur"	Two lines appear
Below CFF	1/2 to 1 line width	Flicker Perceived	Movement from one line to next and back perceived
Below CFF	1-1/2 to --	Flicker Perceived	Flicker Perceived

in the center of the PPI display would move 1/8th of the display height between scans with a scan interval of 1 second and an aircraft speed of 1,000 ft per second. If the image from one scan were not completely erased by the time the new image is painted, considerable image smearing would result. Simple adjustment of the display to provide rapid fade to prevent this smearing will likely result in an annoying fade rate which degrades operator performance in difficult target recognition situations. Slocum et al. suggest line-by-line selective erasure before the writing of a new line to avoid the above difficulties. On faster scanning displays (such as conventional TV) - any type of erasure or phosphor fade is acceptable as long as it is sufficiently fast to prevent smearing of rapidly changing images.

Grain Size

Granularity or grain size refers to the size of the individual elements or components making up a composite image. Depending upon the nature of the sensor and the display system, there are two basic types of granularity. One type occurs when the granularity is super-imposed upon the image during production or reproduction of the image itself. This is observed in certain photographic and printing processes. The second case occurs when the image is "made-up" of grains, as is the case with certain electronically produced imagery. The latter case will be briefly addressed here.

The subject of display granularity has received relatively little attention, but based on the few data available, the subject appears to warrant further consideration and study. Part of the reason for the lack of attention in this area may be due to the fact that granularity has traditionally been associated with the field of photography. Indeed, considerable literature has been produced addressing photographic granularity. Photographic image quality, however, is not within the preview of this effort. Consequently, the subject is included here only to stimulate an awareness of this parameter.

Bennett, Winterstein, and Kent (Ref. 27) conducted an experiment to gather data on the effect of resolution and granularity on rapid recognition performance with well-trained subjects using realistic materials and tasks. They trained 24 subjects (10-12 hours training per subject) on photo-interpretation tasks and had them identify objects (aircraft, towers, trucks, etc.) under several conditions of deresolution granularity and scale size. Their results are summarized in Figure 170. This figure demonstrates the effects of the four grain sizes examined in this study on search time. Bennett et al. conclude, based on the measured average grain size and estimated viewing distance, the point at which grain is large enough to produce poor performance is only about 20 seconds of visual arc. The physical size of the grain producing degraded performance and the rather drastic nature of the drop in performance suggest that granularity or it's

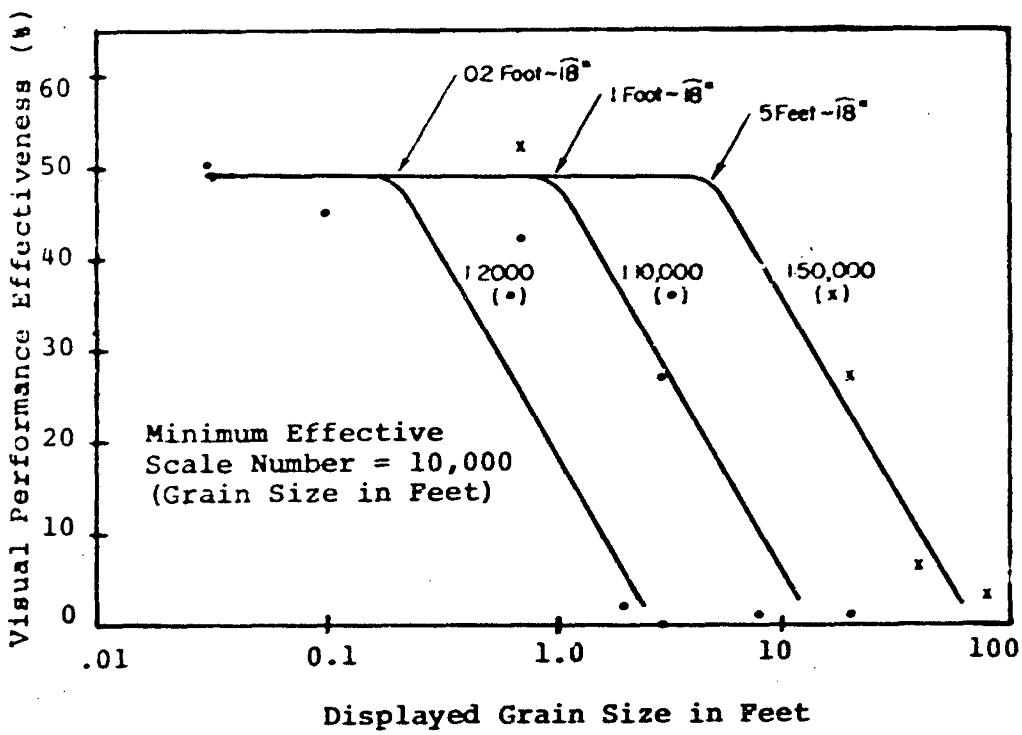


Figure 170. Effectiveness of Visual Performance as a Function of Grain Size and Scale. (After Bennett et al., Ref. 27)

CRT equivalent may be an important display consideration. Further examination of this parameter will be required before concrete conclusions can be drawn.

Summary

The legibility of electronically generated display imagery has traditionally been addressed in terms of the number of active scan lines per symbol. A number of other factors, however, contribute to the legibility of these symbols. Representative factors in this latter class include edge gradient considerations, display jitter and image smear and grain size considerations. These latter factors have received relatively little attention in the literature, although their effect on symbol legibility apparently could be significant.

Edge gradients, for example, affect the sharpness or "definition" of an image, which is especially critical in cluttered or "hazy" displays. Additionally, display search time is affected by edge gradients. Jitter affects the definition of the presented symbology as well as contributing to "unstable" symbology. The effects of image smear is especially prominent in displays with relatively rapid information update rates while grain size, although not significantly examined in the present context, appears to directly influence the observer's performance.

SECTION IX

FLICKER FACTORS

INTRODUCTION

The sensation of flicker is produced by continued intermittent stimulation of the visual mechanism over a limited range of alternations (Ref. 226). At frequencies below 3 hertz, this foveal stimulation is generally referred to as flashing and is often effective as an attention-gaining device. Above this frequency, however, initial or "course" flicker is detected and may result in undesirable observer reactions (disorientation, nausea, visual fatigue, distraction, and annoyance). With increasing frequency, this flickering sensation becomes "finer", and the eye is less able to distinguish individual flashes, until they are no longer detectable. The frequency of stimulation at which the sensation of flicker just ceases to be noticeable is termed the "critical fusion frequency" (CFF), or the frequency at which the properties of the eye (persistence of vision) integrate the individual stimuli to produce the sensation of steady light or of smooth movement. This integration process results from the retention of the stimulus sensation by the visual mechanism for brief periods of time after the stimulus is removed. These retained sensations gradually disappear taking approximately 0.1 second to disappear completely.

The human eye is part of the visual display system, and, consequently, a number of individual differences interact with a number of display parameters to determine the precise frequency at which fusion will occur. This man-display interaction will also vary from one environmental setting to the next, again depending upon the observer and the type of display. Representative of some of the individual differences affecting the detection of flicker are:

Persistence of vision fluctuations
Foveal-cortex characteristics
Chromatic-spherical aberration effects
Individual age, sex, alpha rhythm characteristics

In addition to the above, a number of other parameters affecting the observer's detection of flicker includes:

The area of fovea stimulated
Eye adaptation level
Display, surround and ambient illumination levels
Light-to-dark ratio of the flashes

A large number of display parameters are known to affect the presence of flicker on electronically generated displays. A review of the literature, however, failed to produce a consensus as to just which parameters should be included in this listing. Table 83 indicates this diversity of opinion (and of terminology), but it also indicates that several determinants appear to be common to a number of the reports reviewed. These include:

- Phosphor characteristics - decay time and spectral characteristics
- Display refresh rate
- Information up-date rate
- Viewing distance in relation to display size
- Emitted luminescence intensity and contrast
- Wavelength characteristics of emitted luminance
- Luminance of light source

Flicker, itself, has a number of stages, and each stage tends to elicit different observer reactions. Barmack and Siniako (Ref. 16) suggest that at less than one cycle per second there may be a cyclic loss of and recovery of dark adaptation. They conclude that 2 to 3 flashes per second is the optimum for attention-getting value, but that 4 to 7 flashes per second will cause some visual discomfort. They found 8 to 15 cycles per second to cause some confusion, loss of performance (unspecified) and in some cases, even unconsciousness. They state that pulsed light, to be perceived as a continuous light, must be generated at a rate above 30 Hertz. However, they found this to be a function of the brightness levels concerned. At 0.01 Ft. Lamberts, flicker fusion frequency may occur at 20 Hertz, but at 100 Ft. Lamberts fusion may not occur until 60 Hertz is reached.

The general consensus is that in the literature flicker does not present a major problem to the display designer. Flicker can be eliminated by increasing the regeneration rate, using longer persisting phosphors or reducing display brightness. However, the tradeoffs that have to be made to eliminate flicker may present severe restrictions for the designer, restrictions that can be best circumvented by a knowledge of all of the factors involved and, more importantly, of the interactions of these factors. This section will address these interactions by first addressing flicker as it affects the observer and some of the observer variables involved (see Figure 171). Attention will then be focused on display parameters that interact with the observer to produce the sensation of flicker. Finally, an attempt will be made (where data allow) to relate observer parameters to display parameters and show possible interactions.

Table 83. Summary of Determinants of Flicker.

AUTHORS / FACTORS			VARIABLES														
	Brightness Ambient Level	Phosphor Persistence	Wavelengths	Size & Location of Retinal Area Stimulated	Visual Field Illumination	Light-Dark Ratio LDR	Frequency of Alteration CPS	Regeneration Rate (Refresh)	Size of Display Area	Stimulus Intensity	Stimulus Size	Eye Adaptation	Subject Age, Sex, etc.	Color	Exposure Time	Other Factors	Viewing Distance/Screen Diameter
Kotchel & Jenney, Ref. 206	X	X	X	X									X				
Luxemberg & Kuehn, Ref. 226			X		X	X	X										
Gould, Ref. 141		X			X			X	X				X				
Gebhard, Ref. 128			X	X						X	X	X	X			X	
Davis, Ref. 102	X	X												X			
Carel, Ref. 58		X						X									X
Anderson, et al., Ref. 8															X		
Burnham, et al., Ref. 55	X			X						X		X				X	
Meister and Sullivan, Ref. 232	X	X	X	X			X		X								
Schade, Ref. 289		X						X									X

OBSERVER CHARACTERISTICS

Individual Reactions

Geldard (Ref. 130) reported that under identical viewing conditions and with moderate illumination, it is possible to find CFF values ranging from 35 to 45 cps among a dozen different observers. This range of sensitivity to the detection of flicker is indicative of the range of reactions experienced by individuals exposed to flicker. Investigations of these reactions have failed to establish any firm conclusions other than the fact that reactions (if any) vary from individual to individual. The major portion of the research in this area, however, has been conducted under low-light level laboratory conditions. Little, if any, effort has been addressed to the examination of display flicker under cockpit operational conditions. In actual airborne operations, other variables interact to alter the individual's reaction to display flicker. A lack of reliable data exists for the latter condition.

Intermittent photic stimulation can also be produced by the rotor blades of a helicopter or by the propellers of an aircraft. This type of flicker (rotor flicker) can detract attention from critical tasks and has been reported to occasionally induce true photogenic epilepsy (which Gastaud, Ref. 128, has defined as "idiopathic epilepsy"). Mercier (Ref. 236) reports that cases have occurred where sensitive individuals suffered epileptic seizures while drive at high speed along tree-lined roads or roads where telephone poles were closely spaced. Johnson (Ref. 185) has even reported a case of epileptic seizure being induced by propeller blades themselves.

Laverne and Johnson (Ref. 391) report that among 102 pilots whose EEGs (Electroencephalograms) were recorded during intermittent photic stimulation, one quarter experienced "difficulties" when flicker was present. Except in rare cases, these difficulties could be attributed primarily to interruption of attention and occasionally to vertigo. In addition to these typical manifestations, helicopter pilots (especially helicopter flight instructors) reported that they experienced marked visual fatigue in formation flying during which they had to look for long periods of time at the rotors of the next aircraft.

It is also possible to produce spatial disorientation in aircraft crewmembers by exposure to flickering light sources outside the aircraft (sun, airport lights, etc., viewed through a rotating body). A second source may be rotating anti-collision lights (red) or beacons on aircraft operated at night. This source of light can be reflected from clouds, wings or cowling to create a complex pattern of flashing lights.

Helicopter and single or twin engine aircraft may produce flickering lights that have been reported to induce flicker vertigo. Ailslieger and Dick (Ref. 2) report that this type of incident is increasing with the proliferation of light aircraft and helicopters. Here, again, response to flicker is dependent upon the person, the situation and the frequency of the flashing light.

Persistence of Vision

The sensation resulting from a visual stimulus does not disappear simultaneously with the removal of the stimulus. Rather, the sensation persists briefly after the removal of the stimulus and then gradually disappears. A number of investigations have demonstrated that this persistence of vision can be altered by inducing changes in several pertinent display parameters. In a recent study, Obert-Thorn (Ref. 257) reports that the total persistence time increases linearly as the log of the intensity of the stimulating light is increased. Porter (Ref. 271) found that the undiminished persistence time (operationally defined as the duration between successive flashes of light at the critical fusion frequency) decreased as the intensity of the light source increased. Hence, increasing the stimulus intensity affects the total persistence time and the undiminished persistence time in opposite manners.

Ross (Ref. 285) reports that changing the light-to-dark ratio (LDR) affected the CFF of a display. He also found that for a given flash intensity level, increasing the flash duration (increasing the light period in the LDR) decreased the undiminished persistence time. Wilkinson (Ref. 355) conducted a study to examine the fusion point time interval between two flashes of light that are just fusing. This period of time is called the two-flash threshold (TFT) and is another measure of the undiminished persistence time. Wilkinson's findings, contrary to the findings of Porter (Ref. 271), but confirmed by the findings of Ireland (Ref. 178) indicate that changes in the intensity of the flashes did not appreciably affect the undiminished persistence time (or the TFT time). Table 84 summarizes some of these findings.

Obert-Thorn (Ref. 257) conducted an experiment to examine the persistence decay curve. Flash pairs were used in which the intensity of the second flash was gradually reduced so that the brightness of the first flash would appear continuous with the brightness of the second flash. When a continuity was achieved, the time for the largest decrement required would be measured, and the persistence plotted in a curve. In this study, the log of the intensities of the second flashes were approximately 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 less than the intensity of the first flash. The two durations of flashes used were 25 and 50 milliseconds.

Table 84. Summary of Findings on Persistence of Vision.

Light (Flash) Intensity	Total Persistence	Undiminished Persistence	Two-Flash Threshold
Increase ↑*	Increased ↑ Obert-Thorn (Ref. 257)	Decreased ↓ Porter (Ref. 271)	No change Wilkinson (Ref. 355)
Decrease ↓	Decreased ↓ Obert-Thorn (Ref. 257)	Increased ↑ Porter (Ref. 271)	No change Wilkinson (Ref. 355)
LIGHT-DARK RATIO			
Increase Flash Length	Not Reported	Decreased ↓ Ross (Ref. 285)	Not Reported

* ↓Indicates decrease and ↑indicates increase in value.

The results indicate that the undiminished persistence (TFT) increased as the intensity of the second flash decreased. Decreasing the flash duration from 50 to 25 milliseconds did not change the rate of persistence decline, but increased the duration of persistence sensation before its brightness appreciably declined. These findings are summarized in Figures 172 and 173 showing the persistence curves for high intensity and low intensity stimulation respectively.

Leverenz (Ref. 214), in addressing the problem of the persistence of vision, suggests that the value of 0.1 second be taken as a guide for use in designing electronic displays. This "rule-of-thumb", however, must be used with an appreciation for the wide variations possible around this figure. Additionally, it must be recalled that these values were derived under laboratory conditions and may not be valid under high ambient illumination conditions. Validation of this latter point is required.

Display Chromicity

The chromicity of a display is determined by the spectral composition of the emitted light (dominant wavelength and purity) which is in turn determined by the type of phosphor or other light emitting material used in the display. Chromicity can be altered, to some extent, through the use of filters. It is, however, the surviving dominant wavelength that determines the psychological attributes of hue and, consequently, the type and intensity of resulting chromatic aberration effects. The consequences of the latter effect are discussed in the section addressing visual acuity.

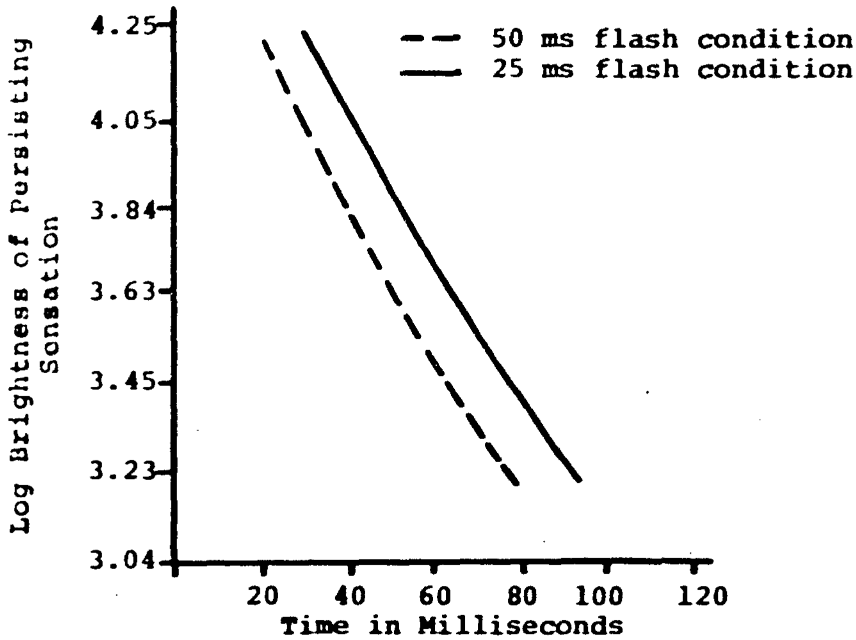


Figure 172. Mean Visual Persistence Decay Curve for-the High Intensity* 50 and 25 Millisecond Conditions. (From Ref. 257)

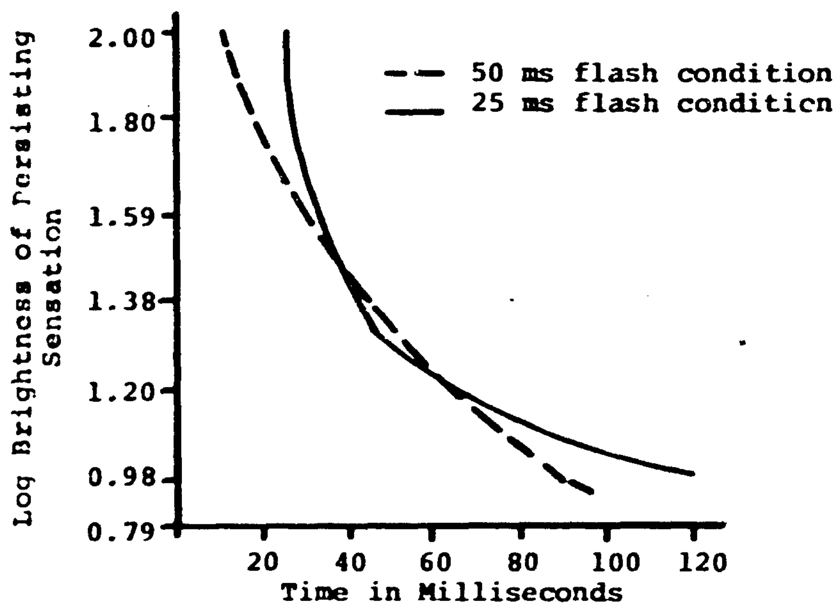


Figure 173. Mean Visual Persistence Decay Curve for the Low Intensity 50 and 25 Millisecond Conditions. (From Ref. 257)

*High intensity stimulus was 2.5 log units greater than the low intensity stimulus (which was not specified). For each of the two stimulus conditions, intensity of background was 2.34 log units below intensity of stimulus.

Gould (Ref. 141) suggests that with all variables, including illumination, held constant, the dominant wavelength of a display is not a critical factor in the reduction of flicker, since the required regeneration rate is independent of the hue when the luminance is held constant. However, because of the spectral sensitivity of the eye and its degraded acuity with certain wavelengths, considerably less energy is required to produce a given luminance level for phosphors emitting in the yellow-green range than for phosphors emitting near the ends of the visual spectrum (Figure 174). Graham (Ref. 145) suggests using wavelengths in the middle of the spectrum (if the display designer is afforded the luxury of choice) for reasons other than the above. Graham points out that visual acuity is poorer at the ends of the visible spectrum than at mid-spectrum, and, consequently, operator performance is likely to be reduced, if end of the spectrum colors are used. Riggs (Ref. 276) notes the nonlinear light emission characteristics of a number of phosphors and suggests that the dominant wavelength of the symbol should be maintained as close as possible to the dominant wavelength of the display background in order to reduce the effects of chromatic aberration.

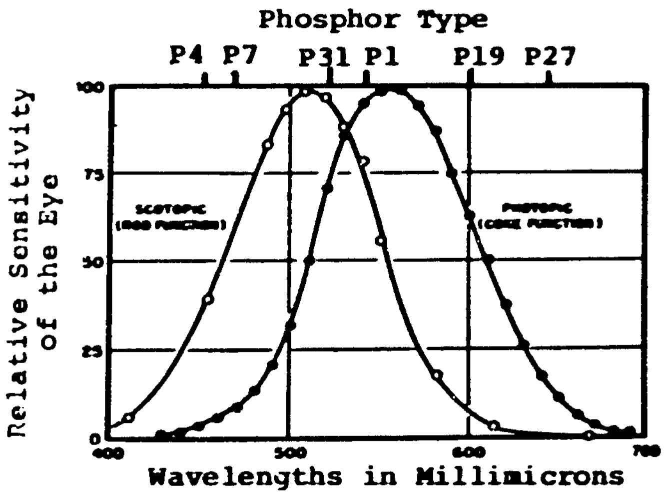


Figure 174. Spectral Sensitivity of Eye Compared to Commonly Used CRT Phosphor Wavelengths.

Turnage (Ref. 332) reviewed the literature and concluded that many of the data pertaining to flicker are not applicable to modern displays utilizing CRT types. Most of the data were collected from low-light level, white light studies and are not valid for today's operating display situations where emitted light is usually not white. Additionally, CRT phosphors exhibit a number of nonlinear phenomena which make it difficult to obtain a combined eye-phosphor characteristic by analytical or graphical methods. Varying decay time, saturation or amplitude distortions, energy-light conversion efficiencies, persistence and color of a phosphor (or other material) are often a function

of the operating temperature, accelerating voltage, beam current density of the CRT and the deflection method employed. As stated above, the color of the luminance emitted from an excited phosphor is a function of the phosphor itself, and, in most cases, it is not white. If, indeed, it is not white, published data on white light CFF are of questionable value for making concrete decisions. Additionally, little or no human factors information is available for the more recent electro-luminescent, light emitting diodes or gas discharge solid state displays with regard to flicker. This virgin area remains to be explored.

Illumination Intensity

One of the basic factors in the control of flicker is the intensity of illumination present in the display situation (retinal, display and ambient illumination). The illumination which is most often treated when addressing flicker is the illumination measured at the surface of the retina. Retinal illumination measurement, however, depends upon the apparent diameter of the pupil and upon the transmittance of the ocular media. Both of these factors are difficult to quantify. Consequently, use is made of a quantity called the "troland" (named after L. T. Troland) which is the retinal illumination (E) computed from the product of the apparent pupillary area (A) in square centimeters times the luminance (B) of the display surface expressed in candelas per square meter (candelas/M^2 x 0.2919=Ft. Lamberts):

$$E = AB$$

The dependence of CFF upon retinal illumination was established over a century ago by Plateau and his fellow workers, but it was not worked out until approximately fifty years ago when Ferry formulated what is now the Ferry-Porter Law. This law states that the critical fusion frequency is proportional to the logarithm of the illumination intensity:

$$CFF = a \text{ Log } E + b$$

where a = a constant
E = retinal illumination in Trolands, and
b = a correction constant

The relationship of CFF to retinal illumination is illustrated in Figure 175 for the simplest case of 100% modulation at a light-to-dark ratio of 1. A review of this figure reveals a relatively large range of retinal illumination levels over which the Ferry-Porter Law is maintained. At any given luminance along this range, however, the CFF will be generally higher for larger display areas (fields). This phenomenon is not linear in nature and, at present, no quantitative expression of this relationship is available. It is known, however, that these curves tend to reverse after reaching a maximum, and that the

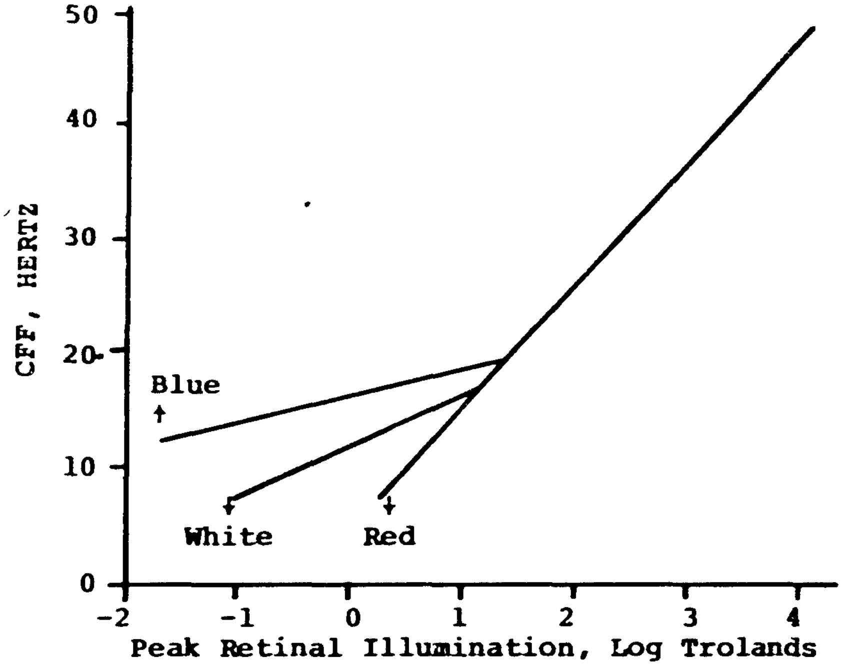


Figure 175. CFF for Varying Retinal Illumination Levels.

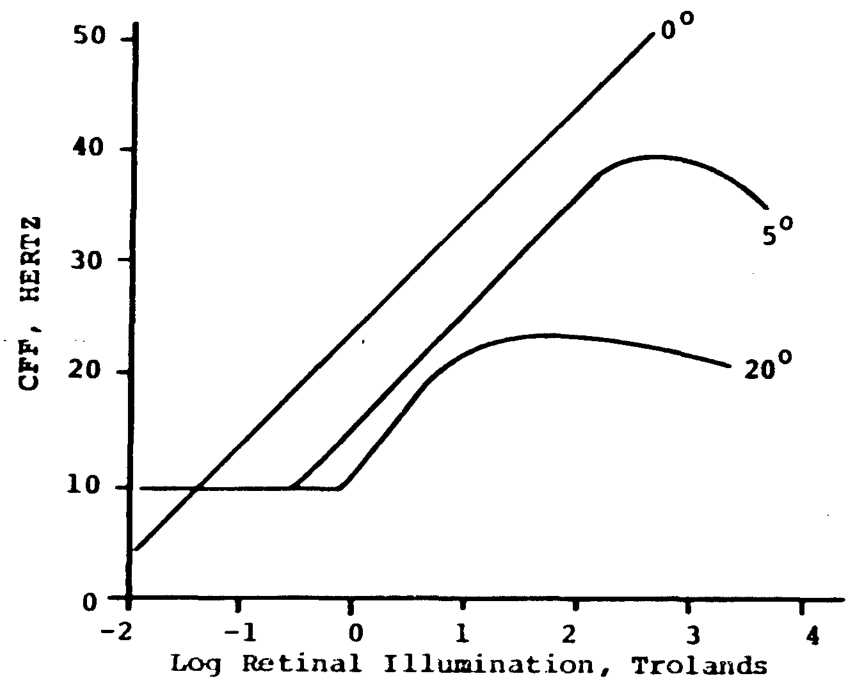


Figure 176. CFF as a Function of Illumination Level for Three Retinal Positions.

tendency to reverse increases with a decrease in the size of the immediately adjacent surrounding non-flickering luminance. Apparently, the greater the area, the more easily the elements may be synchronized, thereby raising the effective frequency of the pulsations in the constituent elements.

CFF will also vary with changes in the angular position of the display relative to the fovea. This is, in part, explained by the fact that all parts of the visual field do not respond to the perception of flicker in the same manner. The peripheral portion of the retina has a different sensitivity to flickering or moving objects than the fovea, and the difference in sensitivity varies with viewing conditions. Figure 176 indicates that CFF varies directly or inversely with the position on the retina stimulated as a function of the illumination level. It can be seen that a transfer from direct to inverse dependence occurs in the vicinity of retinal illumination values of -1 to -2 Log Trolands. Flicker, then, is perceived in the peripheral portion of the retina more readily at low illumination levels and less readily at higher levels. Foveal vision, on the other hand, is less susceptible to flicker detection at low illumination levels than at higher levels.

Bartley (Ref. 20) contends that a steady stimulus applied to one region of the retina will modify the flicker sensitivity in adjacent areas of the eye. Bartley concludes that if a steady stimulus is increased in intensity in one area of the eye, the CFF in adjacent areas is raised until a critical point is reached, at which time the curve begins to reverse. When an increasing low intensity stimulus is applied to the foveal area, the peripheral area sensitivity to flicker will increase until the steady stimulus intensity reaches the transition point from rod to cone vision. At this point, the flicker sensitivity of the peripheral area begins to decline. These conclusions tend to support Southall's position (Ref. 320) which shows the foveal area of the eye more sensitive to higher illumination levels and consequently the transition from peripheral to foveal flicker detection occurs at approximately the transition point from rod to cone vision. The implications of these studies in the design of visual displays are evident. Peripheral and foveal area stimulation are constantly in flux and seldom, if ever, equal in intensity. Consequently, illumination factors other than the immediately concerned display must be accounted for in the design process.

DISPLAY PARAMETERS

Introduction

A review of the pertinent literature addressing display parameters that affect (or interact to affect) the presence of flicker on an electronically generated display (CRT and solid-state) produces a rather long list of factors that should be examined. Examination of each of these factors individually, however, would consume several technically detailed volumes and would not allow for the full appreciation of the impact of the four parameters (display luminance intensity, phosphor characteristics, refresh rate and information up-date rate) that most directly affect the observer's perception of flicker. Consequently, the four factors enumerated above will be examined for salient features that affect the sensation of flicker in the observer and emphasis will be placed on the interaction of these factors with each other and with the observer.

The display refresh rate is one of the primary parameters used to eliminate the presence of flicker on the face of a display. There are, however, a number of other factors that must be considered in establishing the refresh rate for a display and these factors must often be traded-off with the refresh rate in order to achieve the overall system objectives. Some of these factors include the amount of information that must be presented, the rate at which the information must be up-dated, the visible light environment in which the display is to be viewed, the emitted luminance of the display and the scanning method (interlaced, non-interlaced, raster or line written) used. These considerations are, for the most part, restricted to the CRT type of display since the solid-state displays have relatively high refresh rates to start with. Additionally, solid-state displays have almost instantaneous rise and decay time, coupled with rather high emitted luminance levels which necessitate the high refresh rate normally associated with these displays. No data, how ver, have been found addressing refresh rate and flicker on solid-state displays.

Emitted display luminance is one of the determinants of refresh rate and is in turn determined by the type of display (CRT or solid-state), the emitted luminance requirements, the amount of information presented on the display face, and a host of other factors. Essentially, however, it is observed that increased emitted luminance results in increased CFF and consequently requires higher refresh rates.

The display information up-date rate (the rate at which the information is presented or changed) directly affects the brightness of the display and consequently the refresh rate requirements. The up-date rate in turn is determined by the type of sensor equipment used (radars, TV, data-link), the pilot

response requirements and response time. In general, the larger the anticipated interval the observer has to respond in, the lower the required up-date rate.

Phosphor characteristics interact to affect the refresh rate (phosphor rise-decay time), the emitted luminance, and the information up-date rate (may result in 'trailing' or smearing if persistence is too long). Phosphor selection is based on a series of tradeoffs with the many other considerations associated with display design. These tradeoffs must take into account the amount and type of information to be presented, the nature of the mission, the observer viewing conditions and requirements and the limitations of the overall display system. Phosphor selection is critical in the design of CRT type displays and in those solid-state displays that use phosphors as energy converters.

Display Luminous Intensity

Most of the preceding flicker data were derived from laboratory studies conducted under typical laboratory conditions which utilized whole field, square wave brightness fluctuations. Current CRT and CRT-type displays do not necessarily operate on these principles, nor would they elicit identical observer responses to the perception of flicker. Raster scan CRT displays, for example, utilize high intensity cathode ray beams that scan at a rate of 10^5 cm sec^{-1} and which produce 'spots' that are excited for about 10^{-7} second, 30 times a second. The excited spot luminance is considerably brighter for brief periods than the average screen luminance (the exact time being a function of the decay characteristics of the phosphor or other material used in the display). Other CRT-type displays have similar characteristics, while certain plasma and solid-state displays have a collection of unique properties (varying cathode luminescence efficiency, edge emission bands, non-linear hue emission qualities, creep phenomena and extremely high flash intensities) interacting in the production of flicker in display situations. The wide variation in the luminous intensity from display to display, combined with the many unique properties of each type of display, makes the generalization of the findings from academic studies of flicker to actual display situations hazardous at best. Carel (Ref. 68) concludes that the best method for the collection of data relating directly to display flicker is through direct observation of the display under actual operating conditions. To date, few pertinent data are available in this regard.

In CRT displays, the emitted luminance of the display is measured by the emitted light energy per unit area of the light source and is generally expressed in Ft. Lamberts. This energy is derived from the moving scanning spot, and the resulting luminance is determined in part by the scanning beam intensity. The moving spot luminance (expressed in Ft. Lamberts) is

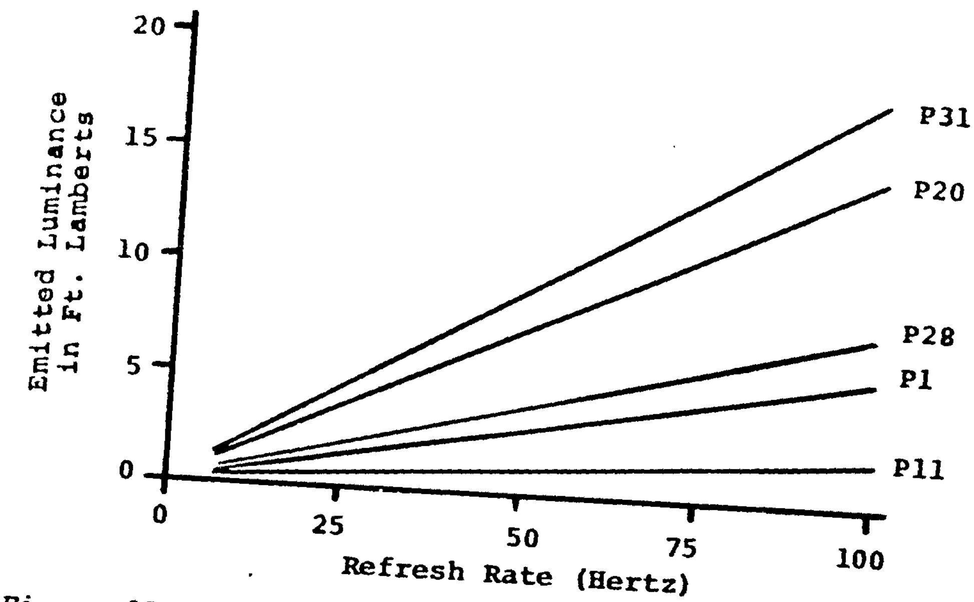


Figure 177. Emitted Display Luminance as a Function of Refresh Rate and Phosphor Type.

expressed by:

$$L_s = KRS^{-a}$$

where L_s = Spot luminance in Ft.-Lamberts.
R = Display refresh rate in cps.
K & a = Constants for a given screen derived from accelerating voltages, current density, phosphor composition, and thickness, aluminizing and light loss in the glass.
S = Writing speed of point in inches per μ second.

Figure 177 presents emitted luminance levels for a number of commonly used phosphors as a function of regeneration rate. It is observed in Figure 177 that the faster the display is refreshed, the less time is allowed for luminance decay (which is a function of the type of phosphor used in the display) and consequently, the greater the emitted display luminance (other factors being held constant).

The display writing speed, in addition to being a function of the regeneration rate, is a function of the amount of information that is being displayed on the screen. The greater the amount of data to be presented, the greater the writing speed required for a given refresh rate. For a further discussion of this topic, refer to references 102 and 226.

CRT brightness is a function of acceleration voltage and beam current. Leverenz (Ref. 214) states that, in general, with other factors held constant, display brightness increases with the increasing acceleration voltage and beam current. However, as the brightness is increased on a display using these two parameters, so does the spot size, and the result is loss of resolution.

In an effort to relate the effects of display screen brightness to the production of flicker, Davis (Ref. 102) examined CFF for a number of phosphors as a function of the display brightness. He concluded that the shorter persistence phosphors (P4, P20) have higher CFF's at any given brightness level for the observer than the longer persistence phosphors such as P7. This is in part due to the fact that shorter persistence phosphors require higher refresh rates in order to produce flicker free displays, and the higher refresh rate generally results in higher display brightness. Also, in general, the higher the brightness, the higher the CFF. This rule, however, is not universal and is subject to exceptions. Sherr (Ref. 301) states that the use of long persistence phosphors (not specified) can reduce refresh rate requirements by 20% for flicker free displays.

Pizzicara (Ref. 267) has indicated that the concentration of phosphor crystals (in grams per unit of squared display surface) has a direct effect on the emitted luminance of a display (EL type and/or CRT type display). If the phosphor layer is too thin, maximum efficiency will not be achieved, but if the phosphor coat is too thick, possible luminance emissions will be 'trapped' in the phosphor layer and the overall emission level will be reduced. Figure 178 shows the emitted luminance for different phosphor concentrations as a function of different refresh rates.

Finally, Carel (Ref. 58) reviewed a study by Schade (Ref. 289) in which direct observation of a CRT display was made under operational conditions. Figure 179 indicates that the flicker threshold is dependent upon the viewing ratio P (ratio of viewing distance/screen diameter), the refresher, and the characteristics of the phosphor decay rate. Schade concludes (Carel) that the regeneration rate is based on the average screen brightness and not on the highlight brightness (maximum brightness above background brightness of a particular image on the screen), provided that the image constitutes only a small portion of the entire screen. If, according to Schade, the average display brightness at the eye was 100 Ft. Lamberts and the viewing ratio (P) was 4 to 5, then the CFF would vary between 45 to 85 cps, depending upon the phosphor used. This is interesting in light of the fact that most other studies reviewed generally tend to have CFF curves that reach an asymptote in the vicinity of 60 cps. Carel states that the issue of the upper limit for CFF "remains unresolved", but it is

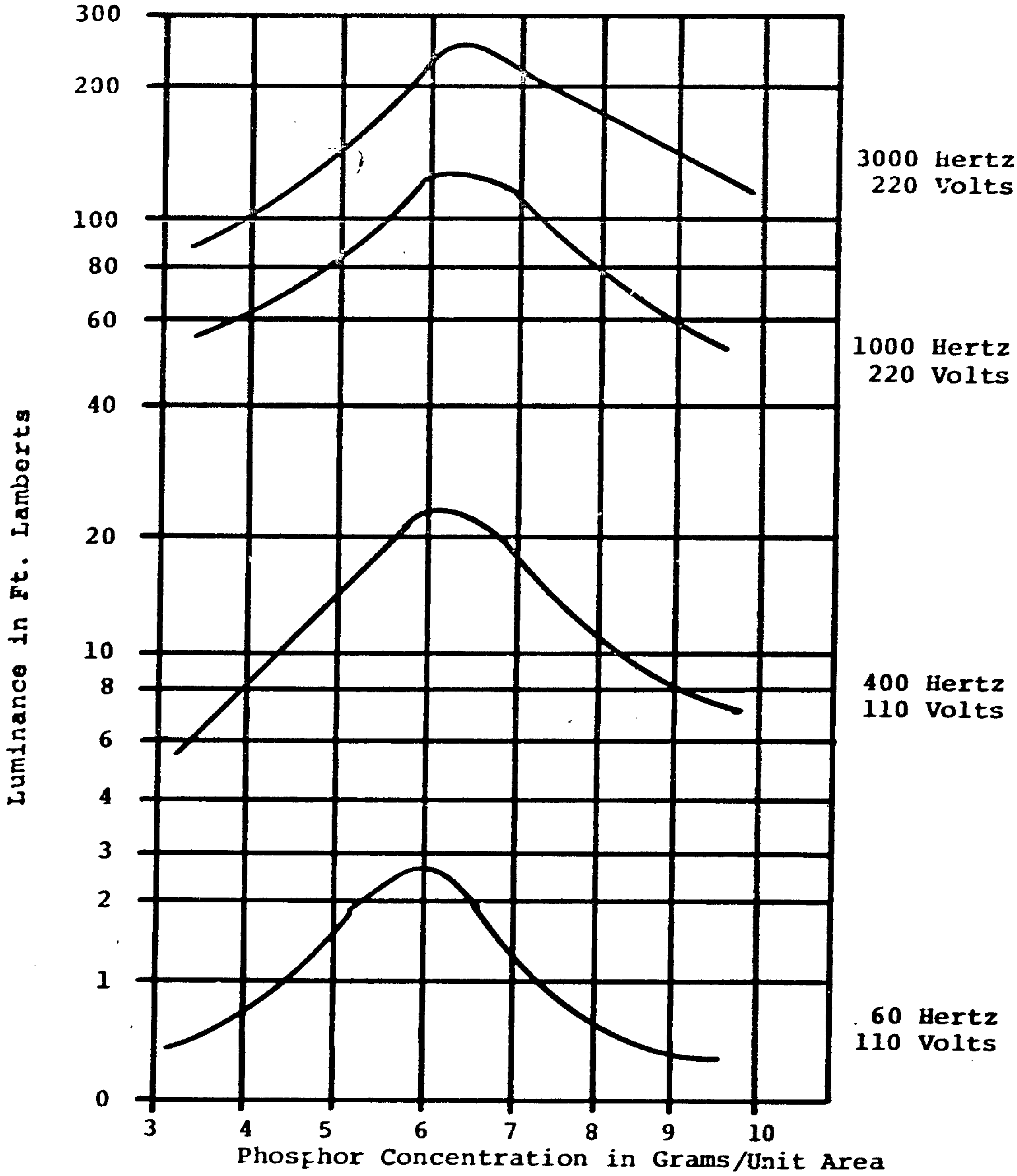
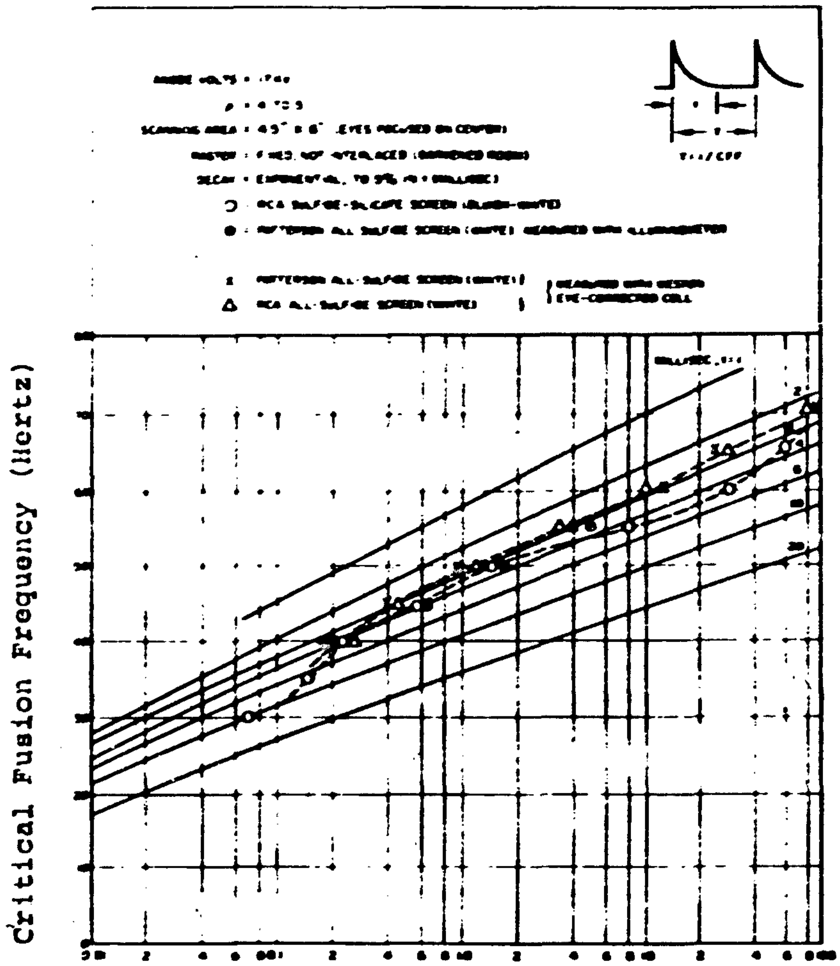


Figure 178. Luminance Output as a Function of Phosphor Concentration.



Critical Screen Brightness (No Symbology) (Bc)
in Ft. Lamberts

Figure 179. CFF as a Function of Critical Screen Brightness in Ft. Lamberts (with Other Factors Held Constant) for White Light. (From Carel, Ref. 58)

of critical interest here due to the requirement to view electronically generated displays under high illumination conditions. To date, there appears to be little or no valid data on flicker under high illumination conditions (up to 8,000 Ft. Lamberts) in operational situations.

Conclusion

In general, the higher the display refresh rate (with other factors held constant), the greater the emitted display luminance. Again, with other factors held constant, emitted display luminance increases with increasing accelerating voltage and increasing beam current. Display writing speed, which is a function of the refresh rate and the amount of information presented on the display, increases as the amount of information presented is increased and consequently reduces emitted display luminance. In general, shorter persistence phosphors have higher emitted luminance levels, partly as a result of the higher required refresh rate for flicker-free displays.

Display Refresh Rate

CRT and CRT-type displays produce flicker because the rasters and the images are written and rewritten by a rapidly moving dot of light which creates a series of light-dark cycles. This cycle, or refresh rate, must be above the critical fusion frequency for the given phosphor in the particular display situation in order to produce a flicker-free (or "fused") display. Several other variables interact to,in part,determine the CFF for a given display (emitted display luminance, phosphor persistence, information density) and thus, in turn, partly determine the regeneration rate of the system. It is essential, however, that the display be maintained flicker-free at all times (even under varying viewing conditions) and for this reason, some 'safety margin' above the critical fusion frequency is required. On the other hand, one of the objectives of the display designer is to keep the regeneration rate as low as possible while still giving the desired performance.

One of the reasons for the use of minimum regeneration rates is that the computer-display system has a maximum bandwidth (in bits per second) and any increase in the refresh rate limits the amount of information that can be transmitted to the display. The relationship between this maximum information rate in bits per second (I_{max}), the refresh rate (F), and the total (binary) number of picture elements (N_D) is:

$$I_{max} = FN_D$$

Because of the reciprocal relationship between F and N, considerable effort has been expended seeking ways of decreasing the required regeneration rate for a fused display. In general, three techniques are used to accomplish this:

1. Rather than progressive raster scanning (such as found on the IBM 2260 display system or two field interlace scanning (as found on commercial television receivers), more spatially complex scanning methods have been studied. These scanning methods essentially attempt to break up the light-dark

illumination cycle produced by raster scanning. Examples of these efforts are Deutsch's (Ref. 106) pseudo-random dot scanning, Pitbaldo, Lincoln and Kaufman's (Ref. 194) dot-line interlace system, and Bell Laboratory's (Ref. 142) phonovision scanning system. Engineering difficulties with some of these techniques are formidable and in some instances, have not been resolved. For further discussion see Ref. 272.

2. Longer persistence phosphors have been used in order to reduce refresh rate. However, some of the characteristics of the longer persistence phosphors (image smearing, image blocking, emission qualities, engineering characteristics) may not be acceptable, particularly for flight displays where higher information up-date rates are required.

3. Finally, by filtering out the short component (the residual light from aberrated sources or secondary emissions) of a cascade phosphor (P7 for example), the overall display luminance level is reduced. With reduced luminance levels, lower refresh rates are required. (It must be remembered that filtering will also reduce total display or emitter luminance.)

Gould (Ref. 141) reviewed the literature and concluded that the commercially accepted 60 cps standard for regeneration would probably be sufficient to prevent the perception of flicker in most electronically generated displays. Gould also compiled the results of several of these studies showing the established regeneration rates for a number of commonly used phosphors (Table 85a). From this table, Gould concluded that the regeneration rate for each phosphor (with the exception of P28) in rank order fashion coincide rather well with the percentage of residual light remaining at specific time intervals after excitation ceases. However, the regeneration rates were not significantly affected by variations in phosphor persistence. His results and conclusions were based on 90% correct identification (rather than the usual 50% threshold).

A comparison of Table 85a and Table 85b (also from Gould) indicates that several of the currently employed commercially available CRT display systems have regeneration rates that fall short of the marginal refresh rates found by Gould.

Crook et al. (Ref. 94) conducted a series of experiments to determine if luminance reintensifications (refresh rates) at frequencies above the critical fusion frequency for a given display were factors in the reading of simulated visual displays. Crook and his co-workers used refresh rates ranging from 40 to 300 Hertz under the same illumination conditions. The results of their studies indicated that refresh rates above CFF had no significant effect on observer performance.

Ketchel and Jenney (Ref. 206) reviewed the pertinent literature and concluded that even with the inconsistencies

Table 85: (a) CFF and Persistence Rates for a Number of Commonly Used Phosphors, and (b) Manufacturer's Specifications for Representative Computer Controlled Displays. (After Gould, Ref. 141)

Table 85a. CFF and Persistence Rates for a Number of Commonly Used Phosphors.

Phosphor	Residual Light after 1/30 sec	Residual Light after 1/60 sec	Persistence to 10% (sec)	Empirically Determined CFF (small fields) (cps): Turnage (1966) 10 ft.L	Turnage (1966) 32 ft.L	Turnage (1966) 100 ft.L	Brydon (1966) 50 ft.L	Mitchell & Resnick (1960) 10 mL	Mitchell & Resnick (1960) 50 mL
P-28	85	90	550×10^{-3}	34	40	46	31.4		
P-19	80	90	220×10^{-3}				17.5		
P-12	70	85	210×10^{-3}	25	29	32			
P-7 (Y)	45	80	400×10^{-3}	32	38	43	29.8 (B&Y)		
P-1	4	23	24.5×10^{-3}	33	38	43	29.2	32	38
P-4	1.3	7	60×10^{-6}	35	41	47	33.5 (B&Y)	36	43
P-31	<1	<1	38×10^{-6}	37	44	51	32.4		
P-20	<1	<1	50×10^{-6} to 18×10^{-3}	40	47	54	32.7		

Table 85b. Manufacturer's Specifications for Representative Computer-Controlled CRT Displays.

Display Model	Phosphor Used	Emitted Color	Display Luminance (ft-L)*	Display/Symbol Contrast Ratio	Spot Diam. (mils)	Regeneration Rate (cps)	Method of Generating Lines	Method of Generating Char.	Display Size (sq. in.)	Number Addressable Points
BR-90	P-4	wh,wh	20	15:1	20	60	stroke	stroke	174.2	1024^2
CDC-250	P-31	gr,gr	-	10:1	35	60	stroke	stroke	144	1024^2
CDC-273	P-7	w,y-g	-	-	20	30	stroke	n/a	322	4096^2
CDC-1744	P-7	w,y-g	-	-	20	40	stroke	n/a	322	4096^2
DEC-338 & 340	P-7	w,y-g	-	-	15	30	point	point	87.9	1024^2
Elliot-4280	L-3,Q-4	org,viol	20	30:1(filter)	15	10	stroke	point	100	1024^2
Ferranti Argus 30 and 40	L-4	org,y	20 min.	4:1	24	16-2/3	stroke	stroke	192	1024 x 768
IDI-10,000 and 11,000	P-31	gr,gr	40	5:1	10	30	stroke	stroke	169	1024^2
III-1050	P-31	gr,gr	-	-	20	30	stroke	stroke	100	1024^2
IBM-2250	P-7	w,y-g	-	-	20 min.	40	stroke	stroke	144	1024^2
ICT-1830	L-3,Q	org,viol	-	-	8	10	stroke	stroke	100	1024^2
IDI-IOM	P-31	gr,gr	40	5:1	10	30	stroke	stroke	169	1024^2
ITT Modular	P-4	wh,wh	40	5:1 min.	21 max.	40	stroke	stroke	144	1024^2
Philco Road	P-28	y-g,y-g	100	20:1	15	60	stroke	stroke	81	1024^2
RCA-6320	P-4A	wh,wh	50	6:1	10	60	stroke	stroke	144	1034^2
Raytheon-1500	P-31	gr,gr	30	30:1	20	48	stroke	stroke	144	512^2
Telefunken 200-4	P-2	y-g,y-g	-	-	-	60	stroke	stroke	400	512^2
SDS-9185	P-31	gr,gr	-	-	20	30	stroke	stroke	100	1024^2
S-C-1090	P-28	y-g,y-g	20	100:1	25	30	stroke	stroke	162	512^2
SEL-80-816	P-31	gr,gr	-	-	14	60	stroke	stroke	81	643^2
Tasker-9000	P-1	y-g,y-g	100	-	18	50	stroke	stroke	227.5	2084 x 1404

*One ft.L equals 1.076 mL.

found in the various studies, some attempt at standardization of refresh rates for electronic displays was still possible. The values they recommend were "reasonably safe approximations" to be applied under standard viewing conditions.

Ketchel and Jenney stated that in the case of the head-up type display, where the background luminance is of high intensity and symbology consists of discrete lines rather than a complete raster, the CFF tends to be lower than it would be if a raster display and a dimmer background were used. They cite an instance where one head-up display was flight tested with a refresh rate of 45 cps and a writing rate of 660 microseconds without evidence of annoying flicker. In this case, green P31 phosphor was used on a display that subtended a 12 degree area of visual angle. They recommend 50 cps as a standard for head-up displays.

For raster type displays with 2:1 interlacing, they recommend the standard 60 cps to be applied to airborne displays.

Ketchel and Jenney add, however, that the above recommendations should serve as guides only and are not intended to be hard and fast requirements for all applications. The display designer should have the freedom to deviate from the standard to achieve goals, but the burden of proof that such deviation will not create adverse flicker is upon the designer.

Meister and Sullivan (Ref. 232) recommend that for character displays, the refresh rate should be greater than 30-40 Hertz. They cite Barmack and Sinaiko (Ref. 16) who state that flicker can be eliminated from most electronic displays if the regeneration (pulse) rate is above 35 Hertz. They add, however, that some flicker is noticeable with average display brightness unless the repetition rate is at least 50 Hertz. These recommendations are for viewing under "normal" luminance levels, and the 60 cps does not hold for emitted luminances above 180 Ft. Lamberts. Meister and Sullivan included a graph of the regeneration rate for several commonly-used phosphors as a function of luminance level (Bryden, Ref. 54), but these do not exceed 100 Ft. Lamberts (Figure 180).

In television, a standard rate of 30 images (frames) per second was chosen because this frequency and the effective rate are related to a-c power line frequency (60 Hertz). This choice of frame sequence rate necessitates less filtering to eliminate a-c ripple (called "hum" in audio systems). With 24 frames per second, for example, rippling that is not eliminated by filtering produces a weaving motion in the reproduced image.

Actually, to eliminate all traces of flicker, an effective rate of 60 frames per second should be employed for TV. This can be accomplished by increasing the downward rate of travel of the scanning electron beam so that every other line is excited instead of every line. When the bottom of the page is reached, the

scanning beam returns to the top of the display to excite those rows missed in the previous scanning. Both of these operations take about 1/30 seconds (1/60 sec. for odd lines and 1/60 sec. for even lines) and since the eye cannot separate the two scans, the effective rate becomes 60 frames per second and no flicker is perceived. This method of television scanning is called interlaced scanning.

Harshbarger (Ref. 159) also suggests the 60 cps be used with the normal 2:1 TV interlace. He points out that the bandwidth, which is the information handling capacity in bits/second, sets the limits of the systems performance. Since bandwidth is an inverse function of the regeneration rate, the latter should be maintained at as low a level as possible in order to maximize the channel capacity. With the standard 525 line format (with time/line T_i = 63.4 μ sec.), the channel capacity should be ideally 4,000 bits/line. With these parameters, 8 to 10 shades of gray will be available for low-resolution detail, but this would be reduced to 3 to 4 for high-resolution detail.

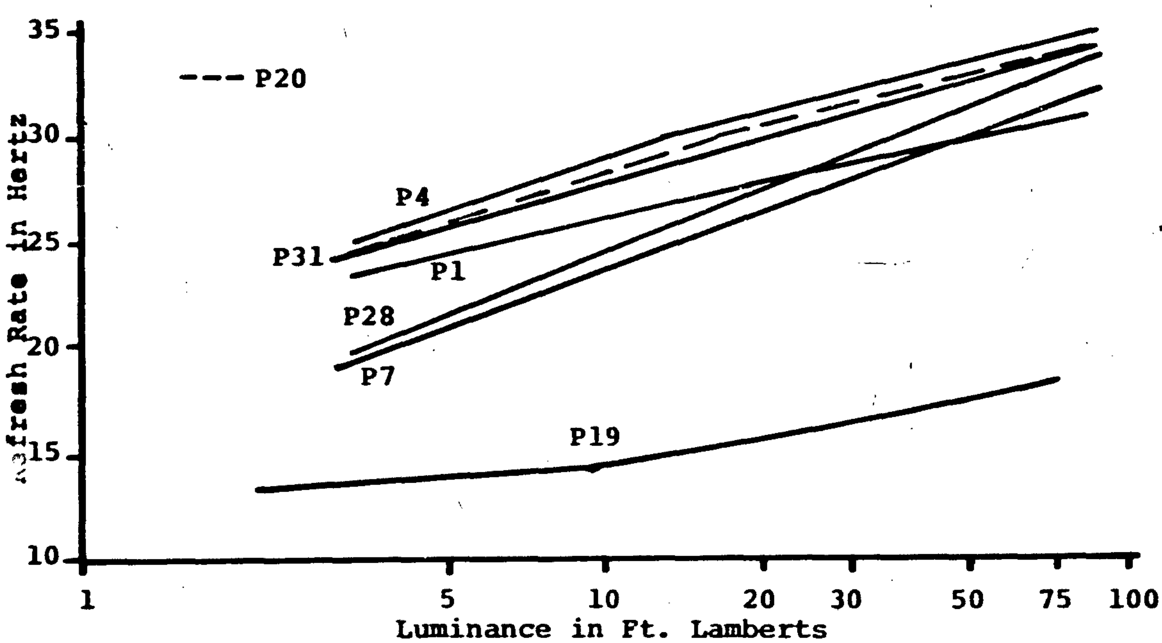


Figure 180. Refresh Rate as a Function of Luminance for Flicker-Free Performance with Several Commonly Used Phosphors.

Barmack and Sinaiko (Ref. 16) suggest that any pulsed light to be perceived as a solid should be generated at a rate above 30 Hertz. The exact rate, however, they concluded was a function of the display situation and particularly the illumination levels concerned. At 0.01 Ft. Lamberts, for example, a flicker free display may be generated at a rate as low as 20 Hertz, but at 100 Ft. Lamberts, fusion may not occur until 60 Hertz is reached.

Humes and Bauerschmidt (Ref. 175), in a series of experiments examining some of the parameters of low-light level TV, reaffirm the general findings and recommendations made by Biberman (Ref. 29) that commercial TV standards are not necessarily appropriate for military use. The results of his experiments led Humes to recommend that a bandwidth of 17 MHz or more be used in airborne military application. He also recommends 1,029 scan lines as opposed to the conventional 525 lines in commercial TV. It is unfortunate that this series of studies did not specify the brightness levels of the experimental condition other than "normal daylight" level. Because of this limitation, the generalization of these findings must be limited. These results do, however, indicate the trend away from the limitations artificially imposed by commercial standards.

Data are not available in the literature addressing the refresh rate requirements for solid-state displays. It would appear logical, however, that because of the unique characteristics associated with these types of displays that flicker does not present a major problem. Currently used AC electroluminescent displays, for example, have refresh rates as high as 400 Hertz and up, so that even with almost instantaneous rise-decay times the eye would have to integrate more than 400 bursts of light over a given second, which is well above CFF for any luminance level. Light emitting diodes (which are primarily DC) have refresh rates as high as 5,000 cps, while AC planar gas discharge displays have refresh rates from 60 cps to over 800 cps. The latter may have a propensity to flicker at the lower refresh rate, but this can be controlled by applying a low voltage DC current to the display which maintains it at a state just below excitation, so that when the AC charge is applied, it is instantaneously excited to its maximum and then decays only to this semi-excited stage.

The above refresh rates appear to be adequate to cope with the relatively high luminance outputs from solid-state displays. On occasion, however, individual emitters or small areas of emitters may appear to flicker on large displays if the separate areas have refresh rates that are slightly out-of-synchronization.

Another unique characteristic of light emitting diode displays is the relatively short (10^{-9} second) pulse duration of each individual flash. It is recalled from the discussion of persistence of vision (addressed in the visual acuity section), that the eye retains the stimulation sensation for brief periods (40 to 100 msec.) after the stimulus is removed, and then gradually allows

it to disappear. In addition, the preceding section discussed the fact that the eye tends to integrate and average the luminance presented in 0.1 second intervals. In light of the two above observer phenomena, it may be concluded that the flash duration is not a contributing factor in flicker detection as long as the refresh rate is sufficiently high to allow the eye to integrate and persist.

In conclusion, results of this review generally indicate that the standard 30 cps, 2:1 interlaced display is indeed the industrial standard, even for military use. Personal communications confirmed that a number of commercially available contact analog displays, head-up displays, etc., use this standard. Additionally, current available handbooks and design guides recommend the above standards. Table 86 summarized these recommendations from a representative sample of these guides.

Table 86. Summary of Representative Refresh Rate Recommendations.

Author	HUD Display	CRT Display	Number TV Lines
Gould, (Ref. 141)	None	60 cps 30 cps 2:1 interlace	525
Ketchel & Jenney (Ref. 206)	50 cps	60 cps	
Meister & Sullivan (Ref. 232)		50 cps	
Barmack et al. (Ref. 16)		30 - 36 and up, depending on luminance level	
Harshbarger (Ref. 159)		60 cps 2:1 interlace	525
Humes et al. (Ref. 175)		Above 60 cps	1,029

On the other hand, no evidence has been found to indicate that the recommended commercial standards have been experimentally evaluated under airborne operational conditions with their inherent high illumination levels. As with the other sections covered in this report, considerable work remains to be done in this area. The research should include consideration of all the parameters affecting regeneration rates. Additionally, creative

experimental research with the many different generating techniques may lead to methods of generating displays without the intrinsic limitations imposed by present television standards.

Biberman (Ref. 29), commenting on the inappropriateness of commercial television standards for military application, notes that there is a fundamental limitation to the information content that can be formed by image tubes at low-light levels (photon noise and manufacturing limitations). He states that this could probably be resolved by increasing the size of the tube, increasing the light emitted from the tube, or both. The basic problem, as he sees it, is the fact that low-light level television is not keeping pace with the capabilities of low-light level sensory equipment.

Biberman concludes that present cameras could produce two to ten times the resolution now transmitted from 525 line, 2:1 interlaced, 30 frame/second camera. The 4 megacycle bandwidth limitation legally limiting commercial television (to avoid TV bands from interfering with each other) need not apply to the military. The military application of this type of display has considerable latitude in this respect. He notes, in conclusion, that the conventional 525 line, 2:1 interlaced, 30 frames/second format is not subject to any major improvements in quality.

Flicker does not appear to be a problem on most of the solid-state type of displays, for as yet, there have been no exploratory or evaluative research studies conducted in these areas. Most of the valid flicker research has been confined to CRT and CRT-type displays, but some basic generalizations can be drawn. One of these is the fact that, if the refresh rate is high enough, the eye will integrate the pulses of light (apparently) regardless of the luminance intensity of the emitted light and the duration of the flash exposure.

Line written displays are similar to raster scanned displays with the exception of the non-systematic addressing of the various areas of the display surface. It is more likely that individual symbols will flicker in the line written display than the display as a whole. This inter-symbol flicker can be eliminated by properly addressing other areas of the display surface.

Light-To-Dark-Ratio

At high frequencies, rapid intermittent stimulations lose their identity and the resulting sensation is that of a uniform luminance equivalent to that produced by a steady stimulus with the same average luminance. This relationship is known as the Talbot-Plateau Law and is mathematically expressed by:

$$L_1 = \frac{1}{T} \int_0^T L_2 (t)\, dt$$

where T = the fluctuation period
L_1 = the equivalent steady state luminance
L_2 = the intermittent stimulus luminance

The Talbot prediction expressed by the above equation has been found to be valid for higher frequencies of flashing light with the perceived brightness being a function of the light-to-dark ratio (LDR) of the intermittent stimulation. Figure 181 demonstrates the relation between the light-to-dark ratio and the perceived brightness. It is observed that the higher the LDR (further away from unity - LDR 1:1), the closer the perceived brightness is to that of the steady state luminance. At lower frequencies, however, a number of interesting deviations are observed. At frequencies between 2 and 18 Hertz, a brightness enhancement is observed which reaches an asymptote in the vicinity of the individual cortical alpha rhythm. The greatest enhancement occurs with a light-to-dark ratio of 1:1 and results in a brightness sensation nearly twice that produced by a steady light source, and four times that predicted by Talbot's Law.

Bartley (Ref. 386) examined the interaction of CFF and light-to-dark ratios, and concluded that rather large changes in the LDR result in relatively small changes in the CFF with the same luminance level. Figure 182 shows the relationship of several different LDRs at a given luminance level. It is observed that the greater the light-to-dark ratio, the lower the overall CFF, particularly for higher luminance intensities.

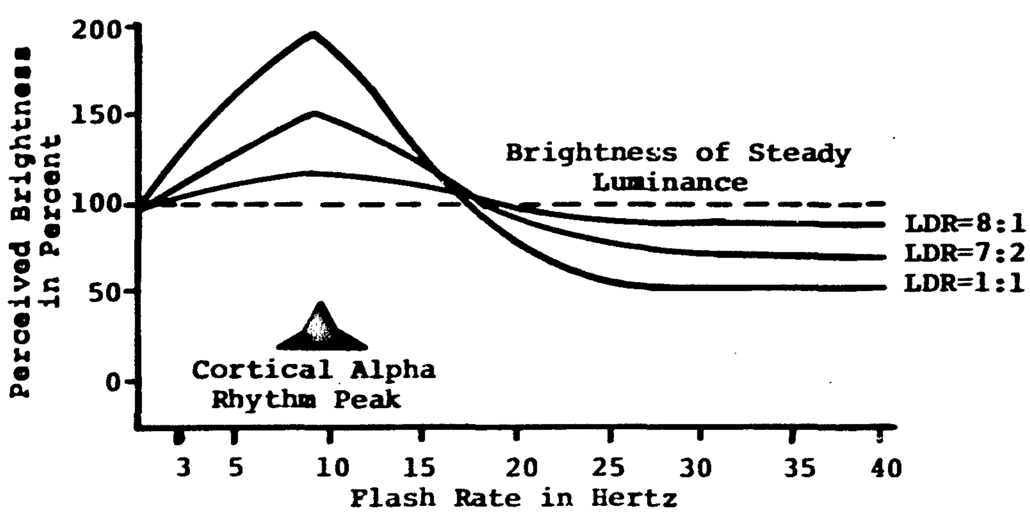


Figure 181. Relationship Between Perceived Brightness, and Flash Rate for Several Light-To-Dark Ratios.

Another aspect of the light-to-dark ratio, the flash duration, also has a direct effect on the CFF and on the apparent brightness of the flash. The effects of flash duration on the apparent intensity of the light source are presented in Figure 183. The data for this figure were derived from a study using a steady light source which was just barely discernable to the observer as the datum reference point with a relative intensity level of unity. The figure indicates that small increases in the relative intensity is required (down to flash durations of 0.2 seconds) for an apparent increase in intensity. For flash durations of less than 0.1 seconds, however, the required relative intensity needed for an apparent change in intensity increases as an inverse function of time. For example, if the flash duration is about 0.003 second, the intensity relative to a steady light must be increased by a factor of 100. The curve in Figure 183 can also be approximated by:

$$E = E_o \left[\frac{t+a}{t} \right]$$

where E = intensity of the flashing source required to appear as bright as E_o

E_o = intensity of the steady light

t = duration of the flash in seconds

a = curve fitting constant equal to 0.21 second

An interesting implication of flash durations of less than 200 milliseconds was observed by Helsen and Steger (Ref. 382). They observed that reaction time to a single light stimulus (S_1) was inhibited by an immediate presentation of a second stimulus (S_2). The inhibition of reaction to the first light stimulus occurred when S_2 was delayed by more than 10 msec., peaked when S_2 was delayed 100 msec., and disappeared when S_2 was delayed by more than 170 msec. Maximum reaction inhibition occurred at about 100 msec. delay and resulted in a 28 msec. reaction delay.

Alpern (Ref. 6) discovered a seemingly related effect in his study of metacontrast. He found that the apparent brightness of S_1 was decreased by an equivalent of Helsen and Steger's S_2 when S_2 was delayed from 50 to 200 msec. Alpern further noted that increasing the brightness of S_2 also decreased the apparent brightness of S_1. It has been suggested by Vreuls and Schmidt (Ref. 338) that these data may reflect different measures of the same time-ordered process of inhibition, which underlies both measures.

Vreuls and Schmidt attempted to examine the nature of this underlying process by measuring reaction times at stimulus intensities that were high enough to drive the probability of detection and response to near unity. Vreuls and Schmidt hypothesized that the inhibition of reaction time shown by Helsen and Steger occurred in the metacontrast stimulus situation.

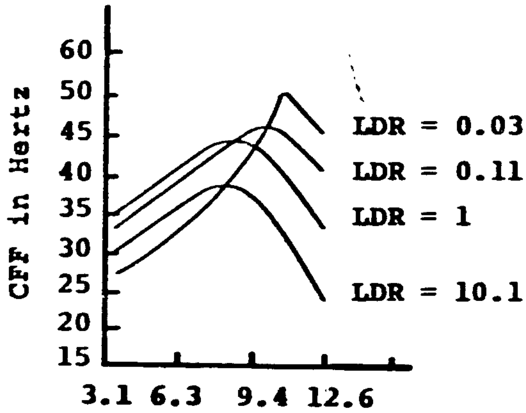


Figure 182. CFF as a Function of Different Light-Dark Ratios. (After Bartley, Ref. 386)

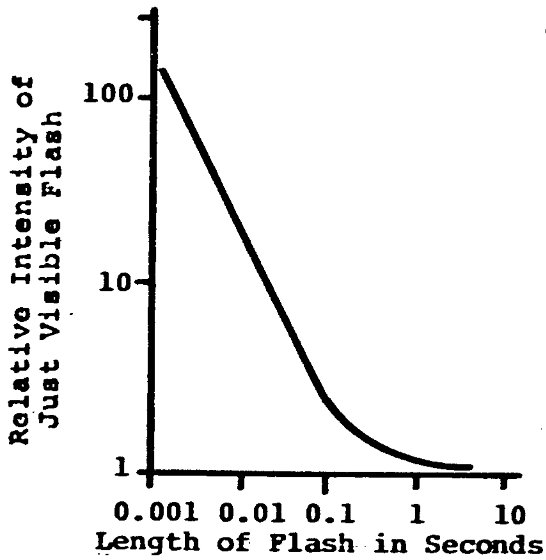


Figure 183. Visibility of Flashing Light Source. (Ref. 33)

Eight subjects (20/20 or better acuity) viewed stimuli presented by two-channel tachistoscope and responded by depressing a microswitch mounted on a flat board. Observer reaction time was measured. Five intervals of delay were used between the presentation of S_1 and S_2 (0, 50, 100, 150 and 200 msec.). The results of the study are summarized in Figure 184.

It is observed that the peak inhibition again occurred at a delay time of 100 msec., but in this study it accounted for only a mean average delay of 8 msec. The mean inhibition was curvilinear ($p < .05$), but was only clearly shown for 6 of the 8 subjects. Additionally, increasing the brightness of S_2 did not increase the inhibition time, contrary to predictions based upon the metacontrast data. (The differences between the Helsen and Steger data and Vreuls and Schmidt data may be account for by the differences in area, raise-time, color temperature and intensity of the stimuli used.)

Anderson et al. (Ref. 8) reviewed a number of studies on light-to-dark ratios and revealed that the slope and the asymptotic values for CFF curves vary as a function of the luminance, light-to-dark ratios, and/or the area of the test patch. Table 87 summarizes some of the findings from their review. Anderson and his co-workers, however, concluded that a number of important variables (surround luminance, light or dark adaptation of the eye, and the pupil size) were not controlled for in the studies which they reviewed. Consequently, they conducted an experiment of their own which attempted to control

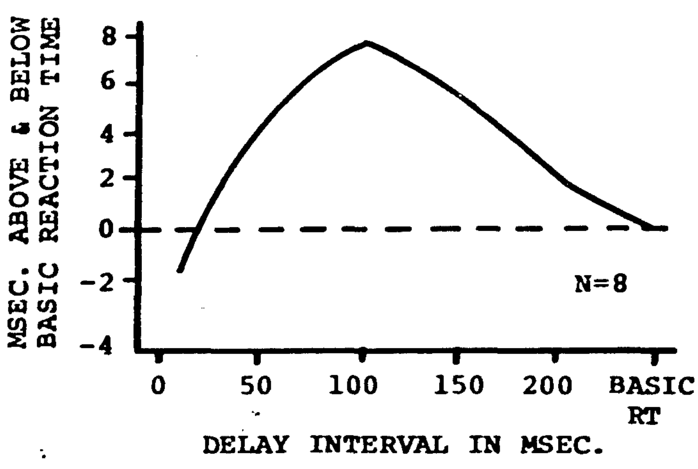


Figure 184. The Inhibitory Effect of a Second Stimulus on Reaction Time to a Primary Stimulus. (After Vreuls and Schmidt, Ref. 338)

Table 87. Summary of Findings by Anderson et al. (Ref. 8)

Variables	Study: Granit and Hammond (1931)	Study: Battersby and Jaffe (1953)	Study: Nelson, Bartley et al. (Refs. 7 and 8)	Study: Anderson, Huntington and Simonscn (1266)
Pulse-to-cycle fraction (s)	0.5	0.2, 0.5, 0.8	0.125, & 0.75 (Ref. 7) 0.17, 0.33, 0.60 0.67, and 0.83 (Ref. 8)	0.1, 0.5, 0.9
Test-patch luminance (in Ft. L.)	120.07, 12.01 1.20, 0.12	34.2	924, 466, 320 (Ref. 7) 16,880, 1688 168.9, 16.9, 1.7 (Ref. 8)	1000 and 100
Visual angle of test patch	1° and 30'	2° and 52'	2° 5' x 45'	0.33°
Surround luminance (s)	0.0065 Ft. L.	Zero (scotopic adaptation)	Not reported (intermittent)	Equated to test patch: 1000, 100 Ft. L.
Exposure durations (sec.)	Total of 11 Range: 0.14 to 1.0	Total of 11 Range: 0.14 to 1.0	Varied continuously (depended upon frequency of stimulus presentation)	0.1, 0.2, 0.5, 0.9, 1.1

for these variables. Results of this experiment are summarized in Figure 185. Essentially, the results show that CFF increases as the flash duration increases from between 0.1 and 0.2 second per exposure under all the stimulus conditions in the experiment (high illumination level of 1,000 Ft. Lamberts, low illumination level of 100 Ft. Lamberts, LDRs of 9:1, 5:5, 1:9 for both illumination levels). Further, a gradual increase in the CFF is observed for exposure times ranging from 0.5 to 0.9 seconds per exposure (under the high luminance condition). Exposures in excess of 400 milliseconds generally did not produce significant increases in the CFF level. Finally, the high luminance levels generally produced higher overall CFF levels for all exposure times and at all light-to-dark ratios.

No data were found addressing exposure durations of less than 100 milliseconds. However, it is known that the retina exhibits temporal integration within finite limits. For example, threshold excitations can remain unchanged while decreasing the luminance of the stimulus if the exposure duration is increased such that:

$$BT = K$$

where B = the stimulus luminance
T = duration of exposure of the stimulus
K = a constant threshold value

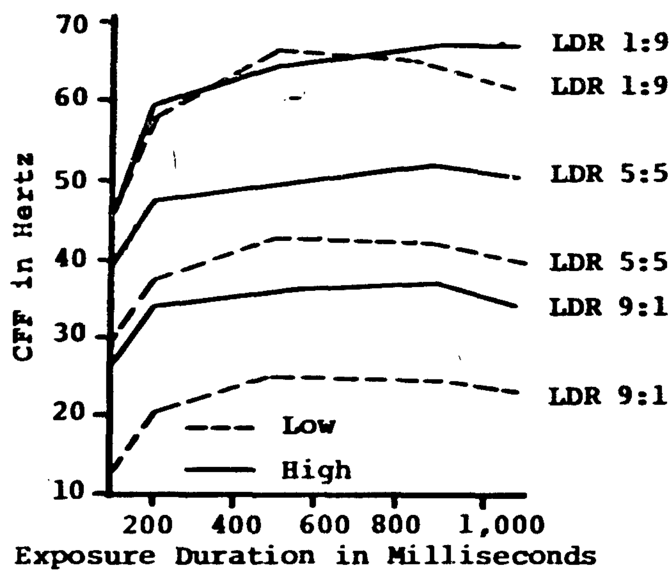


Figure 185. CFF as a Function of Exposure Duration and LDR for High (1,000 Ft.L.) and Low (100 Ft.L.) Luminance Levels. (After Anderson et al., Ref. 8)

This expression is known as the Bunsen-Roscoe Law and is applicable for values of T on the order of 50 to 100 msec. or less. These relationships do not appear to hold for values above the 100 msec. level. However, for periods of time of less than 0.1 second, the product of the time and the contrast is a constant for a given threshold response. This time-luminance reciprocity is a feature of the visual system. That is, the fovea has the property of integrating at each point all of the radiation it receives within the time interval of 0.1 second (Ref. 226). This means that the visual response for short time signals (as might be generated on CRTs or solid-state displays) can be characterized by the integration of the luminance level average over 0.1 second.

The implications of the Bunsen-Roscoe Law may have significant impact on solid-state displays which have high luminance intensities (with almost a square wave on/off duty cycle) with relatively short exposure durations. If a theoretical solid-state system had a refresh rate of 60 cycles per second, there would be 60 flashes per second, and assuming the square wave duty cycle, each flash would have a duration of 1/60 of 1/60 second. But, in accordance with the Bunsen-Roscoe Law, 1/10 of a second would include 1/10 x 60 Hertz or 6 flashes per 0.1 second. Therefore, the perceived brightness would be the average of the brightness of the 6 flashes occurring in the 0.1 second. Increasing the duration of the exposures would increase the apparent brightness of the display, while decreasing the duration of exposure would reduce the apparent brightness. Likewise, the same apparent brightness can theoretically be maintained by simultaneously decreasing the luminance level of the display and increasing the flash duration. No quantitative data, however, have been found to support the above suppositions.

Phosphor Characteristics

A number of phosphor characteristics must be considered in the process of selecting a phosphor for a display (crystal size, life span, burn characteristics, spectral qualities of the emitted light). However, for the determination of flicker producing quality (or flicker eliminating qualities), the phosphor rise-decay time is the primary consideration. A great deal of confusion is evident in the literature with regard to the terminology used in discussing phosphor decay characteristics. Consequently, prior to embarking on a discussion of these characteristics, a brief explanation and definition of some of the terms to be addressed is in order.

Phosphor luminescence is the process of converting electrical energy into visible light, and includes in the process, the excitation (build-up) phase and decay (persistence) phase in a phosphor stimulation cycle (Leverenz Ref. 214). Figure 186 illustrates this cycle and affixes appropriate nomenclature to the various phases of the cycle.

Since it is the emitted radiation from the phosphor crystal which is of practical importance in display design, numerous measurements have been made of phosphor emission qualities, and these measurements have been plotted on thousands of spectral-distribution curves. Unfortunately, not all of these measurements have been made using the same standards or under similar conditions. A large number of parametric variations could affect the data derived from these studies. Leverenz (Ref. 214), however, concludes that the three major factors affecting emission qualities that should be controlled for are: (1) the composite structure of the crystal and the crystal molecule, (2) the kinds and amounts of impurities present in the

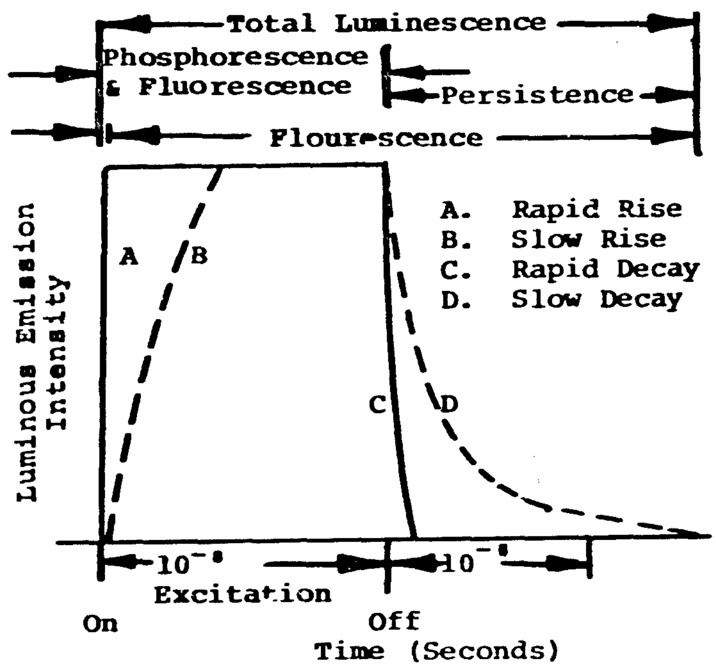


Figure 186. Terminology of Luminescence During Rise and Decay Processes.

phosphor and (3) the thermal agitation (temperature) properties of the excited phosphor.

Gould (Ref. 141) states that the phosphor decay characteristic is the primary determinant of the display regeneration rate, and that it is desirable to have the regeneration rate as low as possible. This results in the propensity to use longer persistent phosphors in displays. (See Figure 187.) However, a number of factors other than persistence rate must be evaluated in the selection of a phosphor for an electronic display. The screen's efficiency, the optimum bias for excitation, the energy requirements for the type of phosphor used and the required brightness of the display surface are but a few of these parameters to be traded-off in this decision. In addition, Luxenberg and Kuehn (Ref. 226) list seven additional requirements that influence the display designer's decision:

1. High instantaneous intrinsic luminance qualities of the phosphor.
2. Stability and life-span under bombardment.
3. Suitable electrical properties.
4. Vapor pressure requirements.
5. Suitable color characteristics.
6. Suitable phosphorescence characteristics.
7. Degree of linear variations of luminance with variations in beam current.

With all these tradeoff considerations, the selection of a phosphor with the desired persistence characteristics is often quite difficult. To compound the matter, certain characteristics of a given phosphor (emitted apparent brightness, C.F.F.) tends to vary from one observer to the next. This makes the establishment of the phosphor characteristics difficult in the first place.

Gibbons and Howarth (Ref. 137), Kelley (Ref. 198) and Turnage (Ref. 332) realized this problem and attempted to use frequency analysis to predict certain phosphor characteristics. They predicted, for example, that phosphors with a relatively high percentage of residual light, following the completion of each regeneration of the display, will have relatively low modulation amplitudes. This same technique has been utilized to establish human performance characteristics of different phosphors. Turnage (1966) decided to extend this method to the eye-phosphor system rather than to each individually. He reasoned that this would be the most reliable measure of the combined eye-phosphor characteristics under conditions prevailing in the operational system itself.

In an experiment conducted to examine the CFF of different commonly used phosphors, Turnage (Ref. 332) examined P1, P4, P7, P12, P20, P28 and P31 under 10 Ft. Candles of ambient illumination incident to the surface of the display itself.

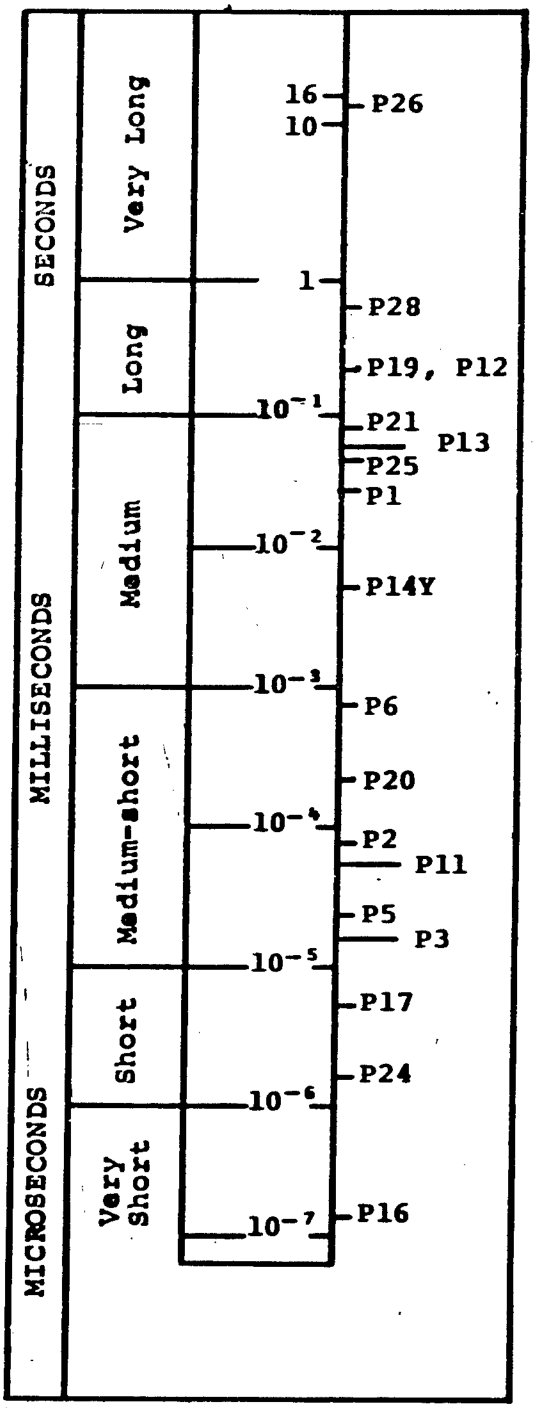


Figure 187. Representative Phosphor Decay Times.

He established contrasts of 5:1 and 10:1, with sine wave and pulse modulation and used characters 5/32 inch high viewed at 18 inches. The data from these tables have been combined and are plotted in Figure 188.

An examination of Table 88 reveals that he obtained CFF values for the human-display system that were substantially lower than those values predicted from laboratory CFF data on humans alone. From this experiment, the phosphors examined have been ranked according to their likelihood to produce flicker in a given situation.

Table 88. Rank Ordering of Phosphors According to their Flicker Producing Qualities. (From Turnage, Ref. 332)

P12	- Least likely to produce in a given situation.
P17	
P1	
P28	
P4	
P31	
P20	- Most likely to produce flicker.

Davis (Ref. 102) reproduced a utility scale showing the relative efficiency of various phosphors with regard to brightness corrected to the human eye. This information is shown in Table 89.

Table 89. Relative Phosphor Brightness Corrected to Human Eye. (After Davis, Ref. 102)

Phosphor	Relative Brightness (%)
P31	100
P32	79
P20	77
P2	76
P28	43
P7	43
P4	43
P1	32
P19	45
P11	10

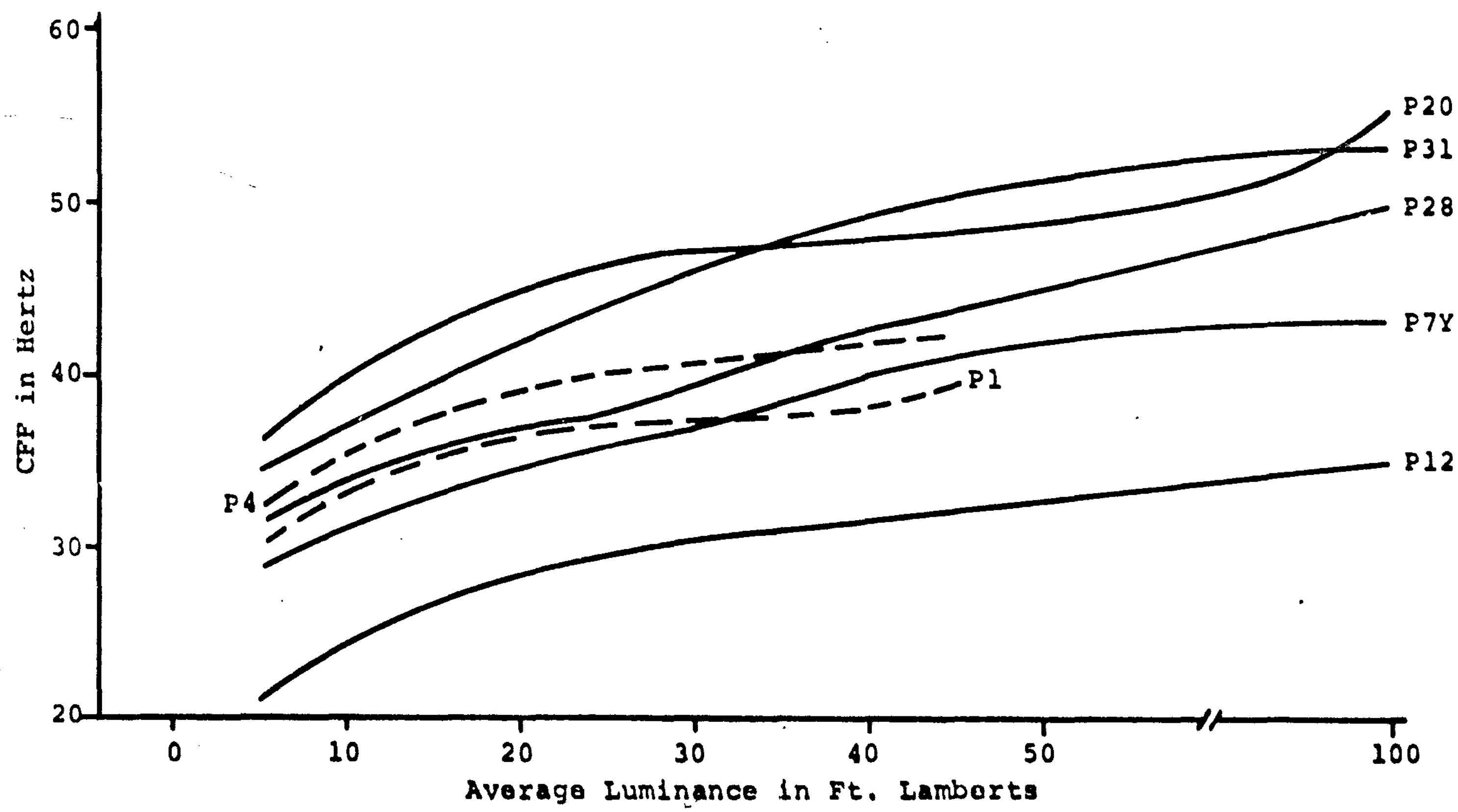


Figure 188. Critical Fusion Frequency as a Function of Emitted Luminance and Phosphor Type. (Adapted from Turnage, Ref. 332)

This type of information is valuable to the display designer working with operational requirements. Unfortunately, no validating studies have been conducted on these results. Additionally, this type of man-variable research has been conducted on a much too limited scale.

Conclusion

The sketchiness of available data on the characteristics of each type of phosphor precludes a comprehensive summation of all of these characteristics. However, an effort is made here to collect pertinent information available on commonly used phosphors.

Based on information supplied by Pyrharski (privately communicated), Luxenberg and Kuehn (Ref. 226) arrived at the following conclusions. The persistence of a phosphor on a CRT screen should be sufficient for observation, but not so long as to cause smearing with changing display information. For most purposes, the short persistence phosphors (with decay rates of less than 10^{-3} sec.) should be used with displays having high regeneration rates of slow image movements. The medium persistence phosphors (with decay rates of not more than 0.1 second) should be used with moderate image movement in order to reduce the possibility of flicker. The long persistence phosphors (above 0.1 second decay time) are best for radar and sonar displays where information change is infrequent (30 seconds up to several minutes apart). These longer persistence phosphors, consequently, require reduced refresh rates.

In addition to the brief summary given above, Table 90 indicates the characteristics of EIA (Electronic Industries Association) registered standard phosphors.

Information Up-Date Rate

An important determinant of the refresh rate for electronic displays is the rate at which the displayed information must be up-dated for the observer-pilot. The up-date rate, in turn, is a function of the nature of the information (highly dynamic or relatively static), the sensor used to obtain the information (radar, data-link, LLLTV), the criticality of the information for mission performance and the observer's time-sharing with other tasks. In any event, the information derived from the sensor or communication equipment must be presented to the observer in sufficient time to allow him to make the necessary decisions and responses.

The relationship of intermittent presentation of information to observer performance is of considerable interest. However, most research involving this type of visual-motor tasks has been conducted with continuously presented stimuli. The actual use of almost all visual displays involves either the

Table 90. Characteristics of Electronic Industries Association Registered Standard Phosphors.

Phosphor	Emission Color: Fluorescence	Emission Color: Phosphorescence	Persistence	Application	Advantages/ Disadvantages
P-1	Yellowish green	Yellowish green	Medium	Cathode-ray oscillographs and radar	High persistence to burn, high efficiency and resolution, lack of low-level persistence
P-2	Yellowish green	Yellowish green	Medium	Cathode-ray oscillographs	
P-3	Yellowish orange	Yellowish orange	Medium		
P-4	White	White	Medium to medium short	Monochrome television picture tubes	
P-5	Blue	Blue	Medium short	Photographic recording	
P-6	White	White	Short	Obsolete--originally used in television receivers	
P-7	White	Yellowish green	Blue, medium short yellow, long	Radar	High efficiency--amber filter must be used for long persistence
P-8	Obsolete	Replaced by P-7			
P-9	Obsolete				
P-10			Dark trace, very long	Outside source of light is used for observation; persistence from seconds to several months	
P-11	Blue	Blue	Medium short	Photographic recording	
P-12	Orange	Orange	Long	Radar	
P-13	Reddish orange	Reddish orange	Medium		
P-14	Purplish blue	Yellowish orange	Blue, medium short greenish yellow, medium	Military displays where repetition rate is 2 to 4 sec after excitation is removed	
P-15	Green	Green	Visible, short ultraviolet, very short	Television pick-up of photographs by flying spot scanning	
P-16	Bluish purple	Bluish purple	Very short	Television pick-up of photographs by flying spot scanning	
P-17	Yellow-white to blue-white	Yellow	Blue, short yellow, long	Military displays	
P-18	White	White	Medium	Low-frame rate television	
P-19	Orange	Orange	Long	Radar indicators	Slow refresh rate for flickerless displays; low-light output

Table 90 (Continued)

P-20	Green to yellow-green	Green to yellow-green	Medium to medium short	High visibility displays	
P-21	Reddish orange	Reddish orange	Medium		
P-22	Tricolor phosphor screen		Medium	Color television	
P-23	White	White	Medium	Low-temperature white--(sepia) interchangeable with P-4	
P-24	Green	Green	Short	Flying spot scanner tubes	
P-25	Orange	Orange	Medium	Military displays where repetition rate is 10 sec to 2 min after excitation is removed	Desired low-level persistence, low-light output
P-26	Orange	Orange	Very long	Radar display	Low-light output
P-27	Reddish orange	Reddish orange	Medium	Color television monitor service	
P-28	Yellow-green	Yellow-green	Long	Radar display	
P-29	Two-color phosphor screen		Medium	Indicator in aircraft instruments	
P-31		Yellow-green	Medium		High efficiency, high resolution

intermittent presentation of information or, as in radar displays, the intermittent receipt of the information by the observer (The man observing the display usually has other tasks to attend to, and, therefore, must share his attention between tasks). The observer, in many cases, imposes his own intermittency (or information sampling) on the display.

Senders (Ref. 295) examined the effects of information presentation rate on observer performance by simultaneously interrupting all components of the observer's task. Eight observers were required to track two pointers, each in a separate instrument. They were scored on the amount of time that both pointers were held within their designated target areas. The dials were illuminated intermittently (but simultaneously) by means of a rotating sector disc in front of the light source. When illuminated, the brightness of the white pointers measured 5mL. Four frequencies of illumination (4, 8, 12 and 20 Hertz) and four light-time fractions (0.05, 0.10, 0.25 and 0.50 where, for example, 0.10 = 1/10 time 'on' and 9/10 time 'off' per cycle).

The results of the study are summarized in Figures 189 and 190. In general, performance increased (in a decelerating manner) with increasing frequency of presentation of the displayed information. It is observed that the score recorded at 20 flashes per second is still considerably below that obtained with steady illumination. This, however, may in part be due to the flicker effect of the flashing light. Likewise, increasing the flash duration increased the performance, but again it was less than obtained with steady illumination. Performance with light-time fraction, however, was more nearly linear than with frequency of presentation variation. This, perhaps, suggests that the duration of the flash is more significant as a factor in observer performance than the number of flashes per second.

Carel (Ref. 58) states that the up-date rate should be at least double the natural frequency of the displayed information, or double the response rate of the pilot, whichever is lower. For example, with a pilot response rate of four cycles per second, the up-date rate for rapidly changing information should be at least 8 cycles per second.

In general, the larger the anticipated interval (the farther ahead the pilot can see in time or space), the slower the update needs to be; and, conversely, the shorter the anticipated interval, the more rapid the information up-date needs to be. At this point, however, the exact nature of this relationship has not been quantitatively defined. It is obvious that a slowly changing data rate with a large anticipation interval would yield smooth operator performance, and vice versa.

In addition to the information requirement for the refresh rate, the phosphor characteristics need to be accounted for.

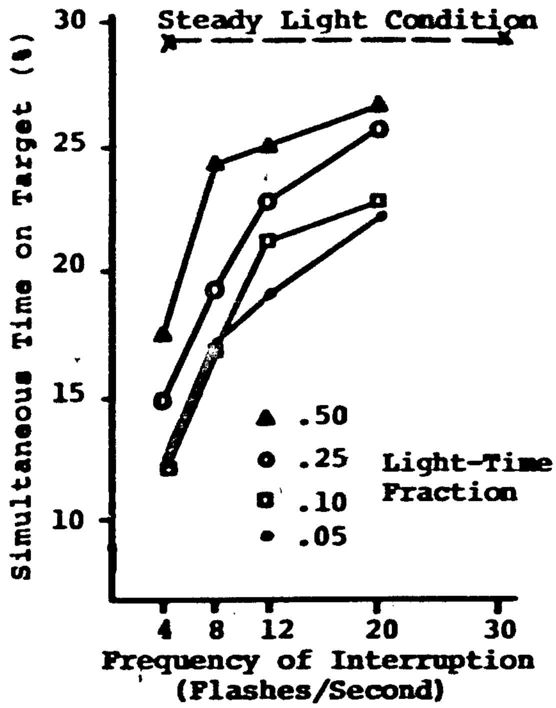


Figure 189. Performance as a Function of Information Presentation Rate. (From Senders, Ref. 295)

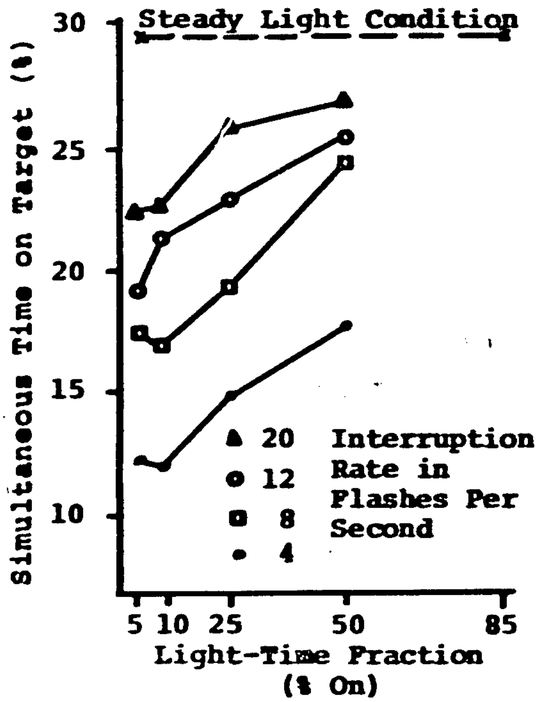


Figure 190. Performance as a Function of Flash Duration (% Time On). (From Senders, Ref. 295)

With a short persistence phosphor and a rapidly changing information rate, a jumping effect could result on the display. On the other hand, too slow a phosphor decay rate could produce undesirably long 'tails' on the moving images or obscuration of smaller images.

From the limited pertinent data available, it can be concluded that observer performance increases as the rate of information presentation of displayed information is increased. At the same time, it appears that observer tasks impose basic limitations on the amount of information received, even if continuous up-dating of the display is possible. This relationship, however, is dependent upon the type and criticality of the task being performed, the nature of the information and the sensor-display system. The precise nature of this relationship is not known and it appears that further research in this area is warranted.

The conclusions and comments made by Carel (Ref. 58) on information up-date rate have obviously been carefully considered and evaluated. They are, however, speculative in nature and have not been experimentally verified. Validation of these conclusions would appear to be warranted, even if only to provide criteria against which to assess proposed standards.

SUMMARY AND CONCLUSIONS

It can be concluded from the above discussion that the prediction of individual CFF is extremely difficult, particularly if a display is to be minimally designed so as to be on the brink of flickering. The following factors should be considered in addressing flicker, however, caution should be exercised in generalizing the parameter ranges below to particular display situations. The burden is upon the display designer to ensure the validity of these values for his display situation. The surest method of doing this continues to be direct evaluation of the observer-display system in the operational setting.

Figure 191 summarizes the effects of flicker on the observer and the different stages of flicker from zero cps to CFF. These values are an approximation for use as a guide only since the values will shift from situation to situation. The critical fusion frequency (dotted line) will vary with:

1. Illumination Intensity - generally increasing with increasing intensity.
2. Size of Display - CFF increases with increasing display size.
3. Area Stimulated - Flicker is more detectable in peripheral vision at low luminance levels.

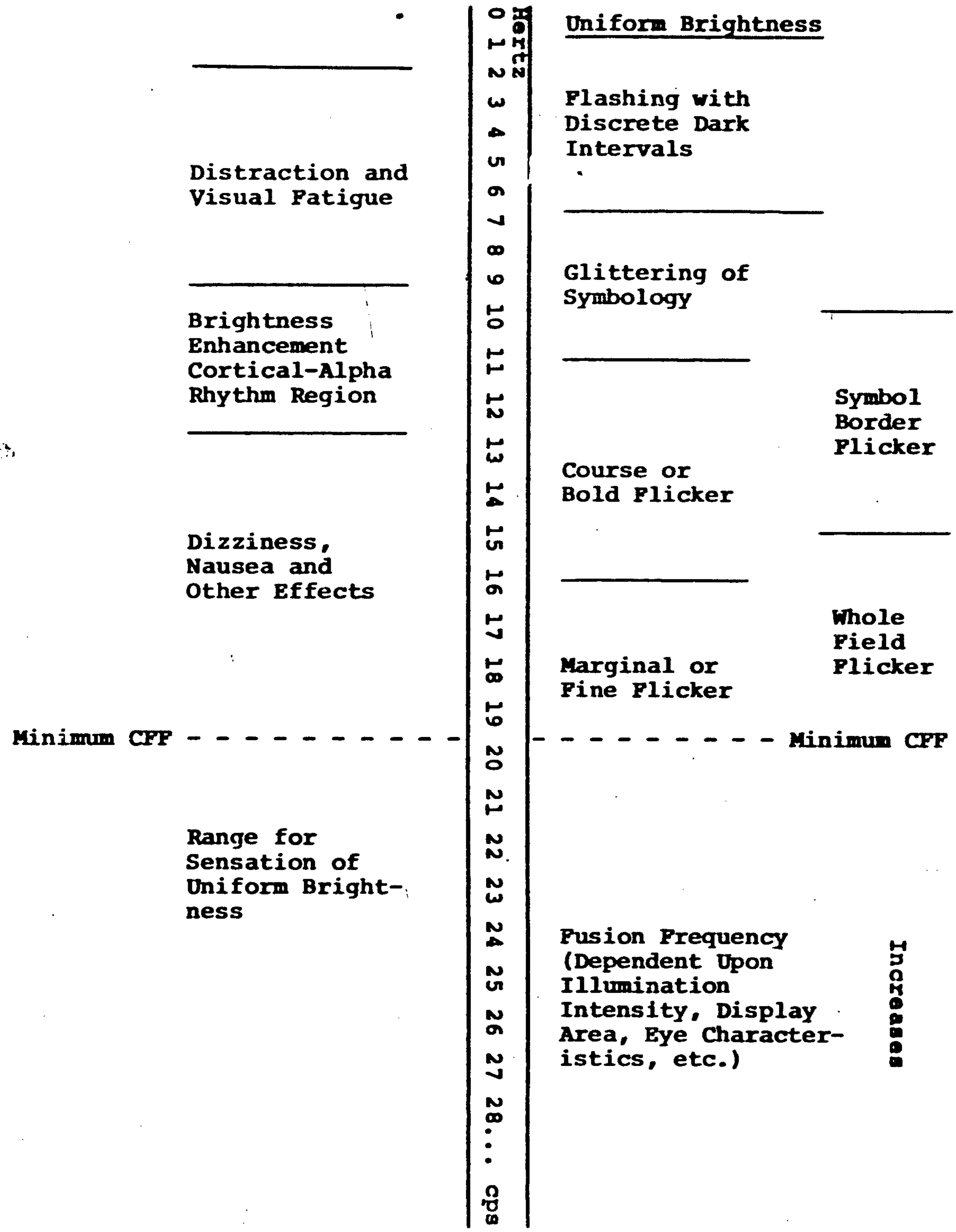


Figure 191. Approximate Flicker Stages and Resulting Observer Reactions.

by central vision at higher luminance levels.

4. Persistence of Vision - Increasing stimulus intensity increases total persistence of vision up to maximum for the individual.

5. Light-dark Ratio - CFF increases gradually with increasing flash duration and with increasing illumination intensity.

6. Non-Flickering Surround- Decreasing non-flickering surround generally increases CFF.

The dominant wavelength of the display (color) is not a critical factor. However, colors in the middle of the visual spectrum require less energy to achieve a given brightness than do colors at the ends of the spectrum. The yellow-green emission region is generally preferred for display purposes, while the blue zone should be avoided. Display target and background colors should be as similar as possible to reduce aberration effects. However, this will work against the maximum development of symbol-to-display contrast.

Flicker is a complex phenomenon which is not completely understood or predictable and which is subject to many different variables in the observer, as well as in the display device. Many valid flicker data exist, but even with this body of information, it is difficult to arrive at any exact determination of what constitutes an acceptable critical fusion frequency. With the advent of high speed computer-display systems capable of outputting large amounts of data in relatively short time intervals, CFF has become even more significant in that it may be the limiting factor in data density for a given display, imposing requirements on deflection and character writing speeds that are extremely difficult to meet.

In order to obtain maximum display output, it is necessary to appreciate the many factors (observer and equipment) that interact in determining CFF. This understanding will allow greater flexibility of design as well as improve observer performance. Table 91 identifies some of the more significant interactions occurring between the observer and the display. Treating the observer and the display as a system in this manner hopefully will allow for a more complete utilization of the capacities of each, as well as allow more freedom in design.

Table 91. Representative Observer-Display Interactions.

Observer Parameters \ Display Parameters	Phosphor Persistence Rate	Emitted Luminescence Intensity	Emitted Spectral Quality	Regeneration Rate	Up-Date Rate	Viewing Distance	Screen Size	Contrast	Light-Dark Ratio	Display Orientation	Surround Illumination	Writing Speed
Persistence of Vision		X	X	X			X		X		X	X
Foveal-Cortex Charact.	X	X	X	X	X		X		X		X	
Chromatic Aberration		X	X			X	X	X		X	X	
Spherical Aberration		X	X			X				X		
Foveal Area Simulated	X	X	X	X	X		X	X	X	X		X
Eye Adaptation Level	X	X	X	X		X	X	X	X		X	X
Spectral Sensitivity Range		X	X	X				X	X		X	
Retinal Illumination	X	X	X	X	X	X	X	X	X	X	X	
Viewing Angle		X	X			X	X	X		X	X	
Brightness Enhancement	X	X	X	X			X		X		X	
Pupil Size		X					X	X		X		
Critical Fusion Frequency	X	X	X	X	X	X	X	X	X	X	X	X

The existing body of flicker data is large and does provide sufficient basis for the making of firm decisions, provided caution is exercised in applications to new situations. It is estimated that flicker-free CRT displays can be designed using the commonly accepted 50 to 60 Hertz refresh rate, even under relatively high illumination conditions. However, displays designed for use under extremely high luminance environments (8,000 Ft. L. and up) would probably require additional validation, if not additional research and experimentation.

The relatively new A-C solid state displays (planar gas discharge, EL, light emitting diodes) have not yet had time to allow for the accumulation of sufficient data upon which to draw firm conclusions. Apparently, little difficulty has been encountered with these types of displays with regard to flicker. The high excitation rates presently used with these displays (gas discharge have excitation rates of 60 to 800 Hertz, other types range from 400 to 5,000 Hertz) virtually precludes the presence of flicker, even under high illumination viewing conditions.

Finally, Table 92 demonstrates a number of the tradeoff functions between various display flicker parameters. This table is for use as a guide only and is not to be considered all-inclusive. It was designed to indicate the interactions one parameter has with a number of other factors.

Table 92. Representative Tradeoff Functions.

Parameter Optimized	Increase	Decrease
Refresh Rate †*	Display Brightness	Information Capacity
Phosphor Persistence†	Info. Capacity	Refresh Rate
Display Size †	Total Luminance CFF Bandwidth Req.	Info. Capacity Useable Shades of Gray
Display Brightness †	CFF Aberration Effects	Display Resolution Storage Time
Info. Presented †	Writing Speed Bandwidth Requirements	Brightness
Writing Speed †	Info. Presented	Erase Time Storage Time Uniformity Brightness Resolution
Storage Time †	Erase Time	Brightness Writing Speed
Resolution †		Brightness Writing Speed

*† = Increase

RESEARCH RECOMMENDATIONS

The observer's basic task with airborne electronic displays is the extraction of pertinent information in readily useable format. In order to present the information in a manner conducive to the observer's need, the display itself must be

flicker free. Unlike many of the other areas examined in this report, elimination of flicker from the display does not appear to be a major concern for designers. It is felt by the present writers, consequently, that research efforts would be more fruitful if directed to more pressing problems in the area of display design. However, several possible exceptions exist to the above recommendation. These exceptions deal with the interaction of viewing distance and display size and the basic body of information available to the designer.

It is known that viewing ratio (viewing distance-to-size of the display) is a significant factor in the elimination of flicker, and it is also known that by moving the observer away from the flickering display, the nature of the flicker is changed (flicker will be eliminated or diminished in intensity). The exact nature of this relationship, however, is presently unknown, and consequently no quantitative data exist on this subject. By varying the viewing distance and the size of the flickering display (with other factors being held constant), a quantitative tradeoff function could be arrived at which would allow the designer the flexibility of choice. The performance measure to be sought in this study would be 100% flicker-free displays within the range of values examined. Since normal display viewing distance is 18 to 36 inches for electronic displays, and the normal range of display sizes is from 5" to 9", these values could serve as the ranges to be explored. By holding all of the other parameters constant, most of the interactions from these factors could be accounted for.

A second area that warrants examination, but which is more restricted to the engineering aspect of flicker, has to do with the information presentation with regard to flicker. Considerable data exist on flicker, but are not in readily useable format. Considerable time and effort is usually required to extract all of the pertinent information applying to one particular phosphor-display system. A good workable guide of the interaction effects of all the parameters concerned (both engineering and human factors) would be beneficial to both human factors and display engineers.

Virtually no data exist regarding solid-state display flicker. As stated in the conclusion section, flicker does not appear to present a problem with this type of display. However, a number of important questions remain to be answered. With the almost instantaneous rise-decay time found in many solid-state displays, for example, is it possible to generalize the flash duration (% of on time) and the light-to-dark ratio data from CRT-type displays to solid-state displays? The psychophysical literature has not addressed these areas using such short periods of time (10^{-9} sec.), and, consequently, valid data are non-existent. Additionally, it has been observed that the CFF

rises as a function of the emitted luminance (or other illumination). With the instantaneous, high intensity emission of certain solid-state emitters, the effects of the overall display luminance on the observer's performance can only be estimated. Comparison studies of operator performance and efficiency should be conducted in order to evaluate the effectiveness of solid-state displays as compared with conventional (CRT-type) displays.

SECTION X

LEGIBILITY CONTRAST REQUIREMENTS

INTRODUCTION

A fundamental and very important consideration in the design of electronic displays, particularly for use in the cockpit, is that the brightness of display symbols must be sufficiently greater than general display background brightnesses to produce accurate and quick identification of the symbology. This problem is particularly acute in cockpit applications of electronic displays due to the extremely high values of ambient illumination which may be present in the cockpit and the resulting display "washout" which may result.

It has long been recognized that simply specifying symbol brightnesses is an inadequate approach to identifying requirements for symbol legibility. Rather, it is necessary to identify the degree to which symbol brightness is different from the immediately surrounding display background brightness in order to provide for criterion performance.

A well established and accepted manner for specifying the difference between display background brightness and symbol brightness is through the use of the contrast ratio equation. All data presented in this section center around the specification of the contrast which is required between symbology and the immediate display background required to produce criterion display legibility.

Several definitions of contrast ratio exist in the literature. Unless specified otherwise for particular cases, the definition of contrast ratio used in this section is a form of the basic $\Delta I/I$ equation. The equation, as applied in this report, is expressed below. From a display design standpoint, the utility of the contrast ratio definition is based upon the fact that contrast ratios thus computed may be interpreted as the percent of display background brightness which must be added over and above that brightness in order to produce symbol brightness which will result in criterion operator performance. The contrast ratio used herein and defined below is frequently referred to as "percent contrast."

$$\text{Percent Contrast (PC)} = \frac{\Delta I}{I} \times 100$$

$$PC = \frac{(\text{Symbol + Background Luminances}) - \text{Background Luminance}}{\text{Background Luminance}} \times 100$$

$$PC = \frac{\text{Luminance Emitted by Symbol}}{\text{Background Luminance}} \times 100$$

Predicting display contrast ratio requirements places many requirements upon human factors data. Relationships of the factors is shown in Figure 192 and are discussed below.

- A central factor is the amount of illumination which may be expected to fall directly upon the display face. Determining the illuminance which may be incident upon the display face requires knowledge of at least the higher levels of daylight ambient illumination, as well as the attenuation characteristics of cockpit canopies and windscreens.

- Second, one must know something of the effects which cockpit and instrument panel geometry will have upon blocking of illuminance which may have entered the cockpit environment. Of particular concern in this respect is the location of the display within the cockpit (e.g., a head-up display) as well as the general attenuating characteristics of the cockpit structure.

- Not all illumination incident upon the display face will be reflected. Hence, it is necessary to know the reflective characteristics of the display phosphor and filters which may be used.

- It is unlikely that illuminance incident upon display surfaces or the luminance reflected from displays and instrument panels will be quantitatively similar with the external (sky) luminance to which the pilot's eyes may be adapted. Consequently, it is also necessary to approximate the levels to which the eye may be adapted since sizeable discrepancies between eye adaptation levels and display brightness levels may result in degraded display legibility.

- Finally, one must specify symbology characteristics including size, strokewidth, color and type since each of these factors significantly influence contrast ratio requirements.

It is necessary, therefore, to specify probable ranges for a number of variables in order to provide the necessary context within which to address display legibility contrast ratio requirements. These variables, therefore, include: levels of ambient illumination, levels of eye adaptation, display background brightness, symbol type, size, color, and, finally, symbology contrast requirements. Specification of probable ranges of these factors, in turn, is dependent upon knowledge of the influences of the variables shown in Figure 192.

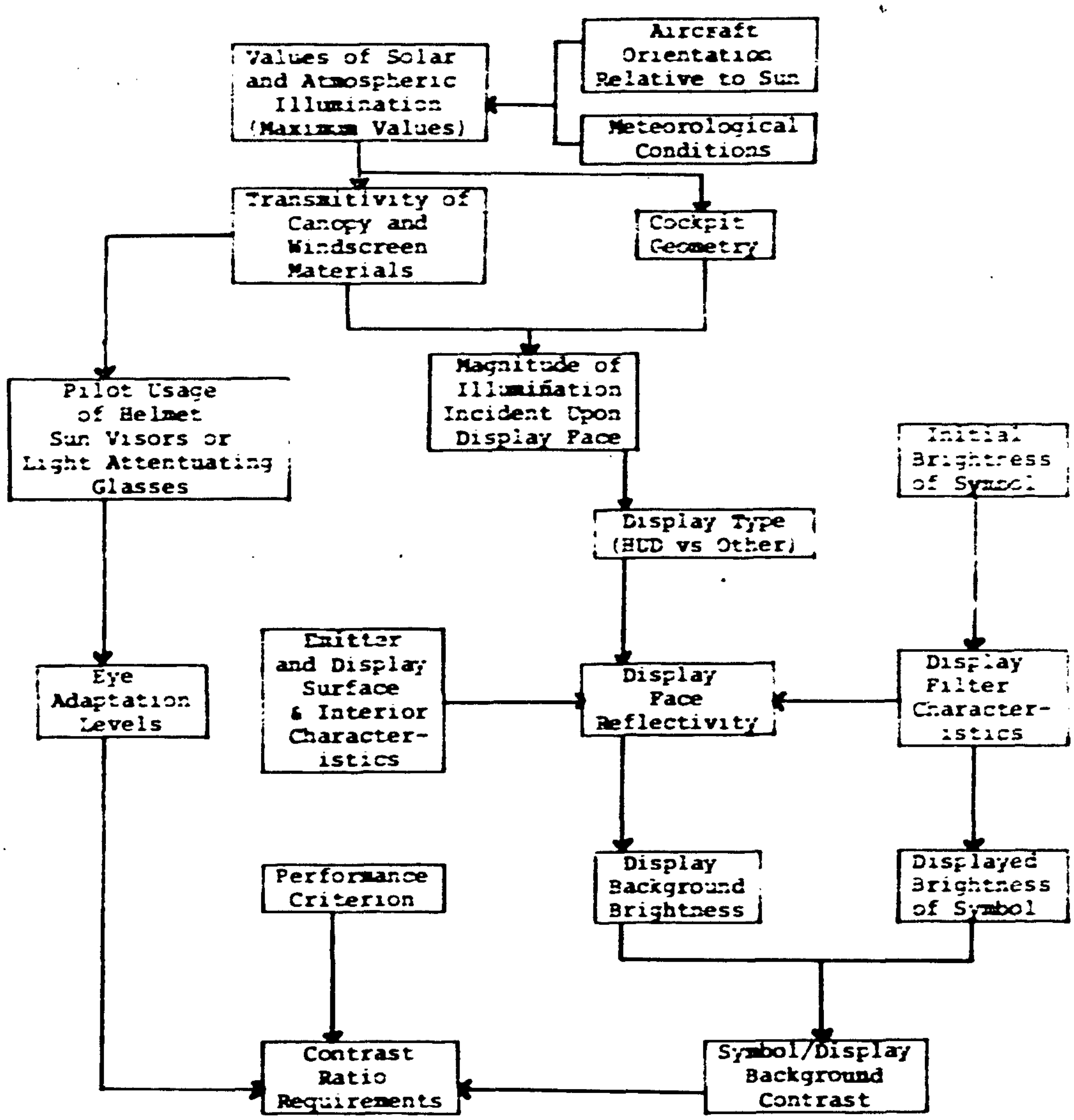


Figure 192. Relationship Among Factors Affecting Symbol-Display Contrast Ratio Requirements.

AMBIENT ILLUMINATION

The subject of ambient illumination is discussed within the report section dealing with environmental variables. Based upon that review, the following representative values are used within this section: direct sunlight at midday is 11,000 Ft. Candles; average luminance of a clear sky is 2,000 Ft. Lamberts; and average cloud cover at midday is 7,000 Ft. Lamberts.

CANOPY AND WINDSCREEN TRANSMITIVITY

Not all light emitted by the sun or reflected by the atmosphere enters the cockpit. This is due to the attenuating properties of canopy materials. The light attenuation by a canopy or windscreen can be affected by the canopy material, state of repair or cleanliness of the material, the angle at which canopy or windscreen sections are mounted relative to a normal line of sight, and the degree to which the canopy or windscreen is fogged by moisture. Considering just new clean and unfogged canopy materials, it has been estimated that a desirable canopy would be one which would transmit approximately 90% of the illumination incident upon it (Ref. 363). Table 92 summarizes acceptable canopy and windscreen transmission and haze limits, and shows how windscreen angle of incidence affects transmission and haze. Considering a maximum transmitivity of 90%, the maximum illuminance which might be expected to be incident upon a display face would be approximately 10,000 Ft. Candles. Other luminances and illuminances cited previously also would be reduced accordingly.

Table 92. Light Transmission and Haze Values.

		WINDSHIELDS INCIDENCE ANGLE					
		55°	60°	65°	70°	CANOPIES	VISORS
HIGHLY DESIRABLE VALUES	Transmission	71%	74%	83%	93%	89%	90%
	Haze	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
ACCEPTABLE IF OTHER FACTORS TAKE PRECEDENCE	Transmission	66%	69%	78%	93%	83%	86%
	Haze	1	1%	1%	1%	1%	1%
MINIMUM VALUE	Transmission	64%	67%	75%	89%	77%	79%
MINIMUM VALUE	Haze	2%	2%	2%	2%	2%	2%

EYE ADAPTATION LEVELS AND SUN VISORS

Many studies which have dealt with contrast ratio requirements for electronic displays have attempted to vary the illumination level to which the pilots eyes are adapted, as well as the amount of illumination incident upon the display face (e.g., Refs. 238, 264 and 265). To make such research meaningful, however, one must be able to answer the following questions: To what range of luminance levels may the pilot's eyes be adapted?; and, What range of illuminance incident upon the display face is associated with varying levels of eye adaptation?

A worst-case answer to the first question may be approximated by identifying the maximum out-of-the-cockpit luminance which the pilot may encounter for extended durations. Based upon the data in Table 108, in the Environmental Variables section, it would appear that this would be the 8,000 to 9,000 Ft. Lambert luminance of average cloud cover at noon (Ref. 344). Obviously, values in excess of this range may be observed. An example is the 82,000 Ft. Lambert luminance of upper surfaces of clouds at noon (Ref. 343). Unfortunately, however, no published data were identified which would provide some insight into the luminance of clouds as a function of the density of the cloud. Thus, little is known about the luminance levels which might be experienced while flying near the top of cloud cover, but not necessarily flight in the very upper surface of clouds. Consequently, such luminance levels can only be approximated at present. In order to be somewhat conservative in light of existing data, it would appear desirable to approximate an average cloud luminance at 10,000 Ft. Lamberts. However, this is purely an arbitrary judgement. It would appear highly desirable to perform the necessary photometric measurements to identify more precisely the range of ambient illumination levels in which both the pilot and electronic displays must operate.

Assuming a maximum eye adaptation luminance of 10,000 Ft. Lamberts, however, ignores pilot scan patterns and the fact that, while flying in clouds, the majority of pilot eye fixations may be within the cockpit rather than outside of the cockpit. Consequently, the pilot's eyes are not adapted to a uniformly luminous surface. Rather, several luminous surfaces may be involved, including the cloud cover outside the cockpit, the cockpit instrument panel, and cockpit consoles. Each of these may vary markedly in luminance level, and it follows, therefore, that the luminance level to which the eye is adapted may not simply be the highest luminance level in the immediate environment. The degree to which this point may be only of academic interest must be questioned, however. If, for example, experimental studies incorporated adapting luminances greater than those which may be encountered in operational settings, a most probable consequence would be legibility contrast ratio

requirements somewhat greater than would be required in the operational setting. Consequently, the contrast ratio would be "over designed" by some small amount, and there appears to be little danger from this. Unfortunately, however, the converse of the situation also may apply, and underestimating luminances to which the eye may be adapted could result in underdesigning the contrast ratio. In this respect, it is fortunate that, in an applied setting, differences in luminance between display background and the surrounding luminance to which the eye may be adapted are of little practical consequence until the surrounding luminance is at least ten times greater than the lowest display background luminance (Ref. 58). Consequently, there would appear to be some latitude for imprecision in identifying luminances to which the pilot's eyes may be adapted. However, this latitude is not infinite.

A recent study (Ref. 179) has directly addressed the effects of the eye being adapted to luminance levels greater than the luminance level of a display background. Figure 193 summarizes salient findings from the study by relating the shift in threshold contrast requirements to the ratio of the luminance of a simulated display background to the luminance of a larger surround area (simulated sky luminance). Results of the study are in keeping with Carel's comment (Ref. 58) that as long as the luminance of the general background surround area (and, hence, eye adaptation level) does not exceed ten times the display background luminance, symbol/background contrast ratio requirements also are not markedly different from conditions in which the surround luminance level is equal to or lower than the display background luminance. It can be seen in Figure 193, however, that minimum legibility contrast ratio requirements rise sharply when general surround luminance (and, consequently, eye adaptation level) exceed approximately ten times the display background luminance. Caution must be exercised in directly applying the data in Figure 193 to display design since the data were collected in a task situation in which subjects were required to detect the orientation of an extremely small Landolt-C ring gap (1.93 minutes of arc). Thus, the data were not collected in a directly applied display task setting, but rather in a visual acuity task context.

A final and very significant factor affecting eye adaptation level involves the use of helmet-mounted sun visors or other optical filtering devices such as sun glasses. There is no known Air Force operational procedure regarding the use of helmet-mounted sun visors or sun glasses with the exception that sun visors are to be drawn down over the face during ejection. What is known, however, is that there is tremendous individual variation in the use of sun visors. Some fighter pilots use them quite frequently, while others insist that they never use the helmet-mounted visor. Similar variation in individual preference is found in the use of sun glasses by cargo or bomber pilots.

The most pronounced effects which visors or sunglasses have, of course, involves the change in surround luminance level to which the eyes are adapted. Similarly, apparent display background luminance is reduced as is apparent emitter (symbol) luminance. Contrast ratio, per se, is not affected. Other factors, however, also must be considered. No sunglass or visor is a perfect optical transmitter. Accordingly, symbol resolution may be degraded. Additionally, the lenses of Air Force sunglasses and visors are green in color. In other words, they transmit more energy in the wavelength regions corresponding with the color green, while attenuating other wavelength light to a greater extent. Consequently, the actual reduction in apparent brightness of an emitter (symbol) will vary as a function of the wavelength composition of the emitter luminance when visors are worn. Finally, the use of sun visors or sun glasses may result in a loss of color contrast between symbology and display background. It is to be anticipated that this problem would be most pronounced for green symbology. This follows since the use of visors would result in the eyes seeing green symbology against a display background which would be imbued with a greenish appearance. On the other hand, if the wavelength

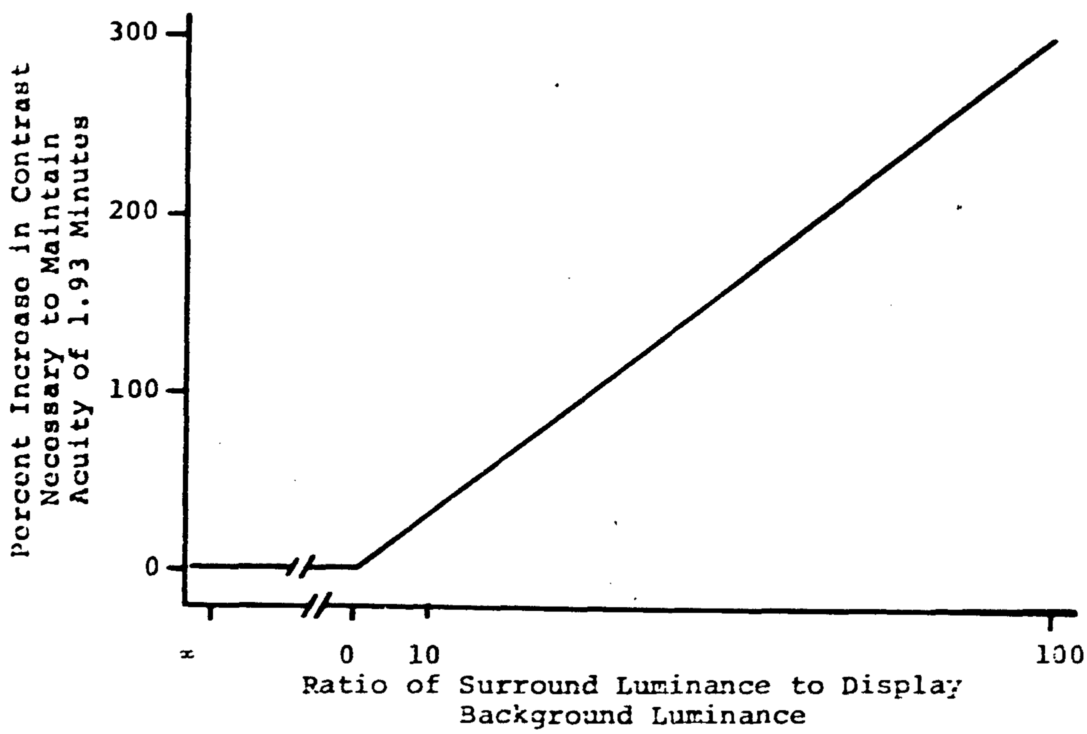


Figure 193. Percent Increase Required in Contrast Ratios as a Function of the Ratio of Surround Luminance to Display Background Luminance. (Adapted from Ref. 179)

composition of display background luminance could be controlled in a fashion which would result in the visor's attenuating heavily at that wavelength range, then both color contrast and brightness contrast might be enhanced.

The questions remain, what are the effects of sun visors and sun glasses upon display emitted luminance and contrast ratio requirements, and are the effects of magnitude to be of practical, operational significance? The literature examining the effects of sun visors or sun glasses upon operator task performance is far from complete or conclusive. The available literature is reviewed below.

In a recent study, King et al. (Ref. 208) measured the transmitivity of operational helmet-mounted sun visors worn by a sample of eleven F-106 pilots. Median transmitivity was 11%. Making the arbitrary assumption that no pilot would lower such a visor into place in the presence of sky or cloud luminances less than 1,000 Ft. Lamberts, it would follow that the lowest daytime luminance level to which the eye might be adapted would be approximately 110 Ft. Lamberts. Assuming that some pilots indeed do not use helmet visors or similar devices, it would follow that the highest level to which the eye might be adapted would be approximately 10,000 Ft. Lamberts, if eye scan patterns are ignored. Because of individual pilot preferences, it may also be anticipated that eye adaptation levels at intermediate values also will be found in operational settings.

There is relatively little literature directly addressing the effects of sun glasses or sun visors upon the legibility of electronic displays under high ambient illumination conditions. Those data which are available are only piecemeal or indirectly applicable to the total range of ambient illuminations and display background brightnesses (and symbol/display contrasts) which may be anticipated or required in the context of aircraft cockpit application.

Allen (Ref. 4) reports a study of visual performance through five opthalmic filter glasses (sun glasses), five identical filter glasses uniformly coated to produce 10% light transmission, and five other identical filter glasses with a gradient density coating transmitting 10% in the center of the lens and about 0.1% at the top of the lens. The five basic opthalmic filters which were made up into sunglasses were Clear, Calobar D, Kalichrome C, Smoke Rose (a former Air Force standard sunglass), G-15 Uniform Gray, and Azurelite 3 which corresponded with the following colors: clear, blue, green, smoke, amber and yellow. An 8 by 24 foot atmospheric (fog) chamber was used. Luminances of the walls of the chamber were either 470 Ft. Lamberts or 7,200 Ft. Lamberts. Three levels of water particulate fog were used: zero, 50% and 75%. One hundred percent fog represented the saturation limit of the chamber. Microammeter measures of a photocell output were made under

the maximum saturation condition, with measure being established as 100%. Measures of fog density, then, were based upon the maximum saturation, and are therefore relative.

Six subjects participated in the experiment, and each subject wore each of the various combinations of sunglasses which had been prepared for the experiment. The subjects had two tasks to perform. First, they adjusted the brightness of a five centimeter test spot to values just noticeably brighter, and then just noticeably dimmer than the brightness of the far wall of the fog chamber on which it was located. When this task was concluded, an auditory signal was presented, and the subject then read a single digit number displayed upon a simulated aircraft instrument panel directly in front of the subject. When the number was read, the subject depressed a reaction time button. Reaction times for correct readings were recorded, as were brightness values associated with adjusting the far field target circle to just noticeably brighter and just noticeably dimmer values.

Allen used the measure "luminance range of far target invisibility in percent", which was defined as the luminance of the 5 centimeter target spot when it was just perceptibly brighter than the wall surround minus its luminance when it was just perceptibly darker than the surround, divided by the upper luminance and multiplied by 100. Consequently, smaller percent values represented greater sensitivity of the eye to brightness change. Data from the study were quite complex and interactive.

Of particular interest, however, were the data for the high luminance condition. In terms of the index of target invisibility, performance was highly comparable regardless of the sunglass which was worn and regardless of fog condition. Mean times required to read numeric values from the simulated instrument panel, however, were consistently shorter for the gradient coated sunglasses. Uncoated or uniformly coated 10% transmitivity sunglasses resulted in consistently greater reaction times, with the increase in reaction time having averaged approximately 50%. Under the low (470 Ft. Lamberts) luminance condition, the results were considerably more complex. However, one trend of interest was that the uniformly coated sunglasses were comparable with the normal glasses in terms of target invisibility. The gradient coated glasses resulted in consistently inferior performance. However, the uniformly coated sunglasses consistently resulted in longer times required to read the number displayed on the simulated instrument panel. Averaging all the recognition times obtained in the study produced the following trend:

	No Sun Glasses	Uncoated Sunglasses	Uniform Coated S.G.	Gradient Coated S.G.
Recognition Time in Seconds	0.599	0.603	0.760	0.506

In a recent experiment, King et al. (Ref. 208) investigated contrast ratios necessary to result in virtually 100% legibility of high contrast electroluminescent bargraph and numeric readout displays. The numerics were 0.4 inches high and 0.28 inches wide, with a stroke width of 0.05 inches. The 125 segment bargraph had a height of 5.0 inches and a width of 0.25 inches. Stroke width for each segment was 0.035 inches, while gaps between segments were 0.005 inches. Contrast ratios required to produce "comfortably bright" displays also were determined. Two types of illumination were used in an attempt to simulate representative cockpit luminances. Under one combination of conditions, a simulated canopy surround was illuminated to brightnesses of 500, 3,100 and 8,600 Ft. Lamberts. Under the second combination of conditions, a Xenon arc lamp was used to produce 500, 5,000 and 10,000 Ft. Candle illumination (measured using a magnesium oxide surface) incident upon a simulated aircraft instrument panel. Under the two higher illumination levels for each illumination source, data were collected both for the naked eye and with the use of helmet mounted sunvisors of 11% transmitivity. Thirty subjects, twenty of whom were Air Force pilots, participated in the experiment. Photometric measurements of display brightnesses were made, and the data were transformed into measures of symbol-to-display background contrast. Display reading time data also were recorded.

When emitted luminance was increased to produce displays which were judged to be "comfortably bright" by the subjects, no differences were found between contrast ratios or display reading times for the with-visor versus no-visor comparisons. However, when emitted luminance levels were only those required to produce three consecutively correct display readings, the use of the helmet mounted visor did show an impact. Mean contrast ratios required to produce 100% legibility for the bargraph display were unaffected by the use of the helmet mounted visor. However, mean legibility contrast ratios, and thus emitted luminances, were consistently greater for numeric readout legibility when subjects used the visor. The differences were statistically significant at the .01 level of confidence. With the visor in place, legibility contrast ratios ranged from 110% to 128% of the contrast ratio required without the visor, depending upon illumination source and intensity. Also, mean time required to read each display was significantly longer in three out of four conditions in which the sun visor was used. The data are shown in Table 93. In a separate comparison, these data were adjusted to take into account the fact that the use of the visor reduced the apparent display

Table 93. The Influence of 11% Transmitivity Visors Upon Legibility Contrast Ratio Requirements for an EL Numeric Readout.

(Adapted from King et. al., Ref. 208)

	General Canopy Surround Luminance Levels in Ft. L.	
	3,165	8,617
Display Background Luminance in Ft. L.	21.1	58.2
Mean Emitted Luminance in Ft. L. for Naked Eye	6.7	14.0
Mean Percent Contrast for Naked Eye	31.9	24.5
Mean Emitted Luminance in Ft. L. with Visor	8.4	18.5
Mean Percent Contrast with Visor	39.8	31.3

	Direct Incident Luminance Levels in Ft. Lamberts	
	5,000	10,000
Display Background Luminance in Ft. L.	103.0	181.2
Mean Emitted Luminance in Ft. L. for Naked Eye	21.5	30.1
Mean Percent Contrast for Naked Eye	20.6	16.5
Mean Emitted Luminance in Ft. L. with Visor	25.1	34.2
Mean Percent Contrast with Visor	24.2	18.2

background brightness. The adjusted data were compared with other data published by King et al. for non-visor conditions. The effects of use of the visor were still apparent for the numeric readout. Similar trends have been reported by Ketchel (Refs. 203 and 204).

Parker (Ref. 261) reports a study in which two subjects were driven down a mile-long runway in an automobile at 25 miles per hour. Their task was to detect the direction (up, down, left or right) of the gap in a large Landot C-ring. Each subject alternately wore a flight helmet with visor transmitivities of 15%, 3% and 1%. Data also were collected in the early afternoon on a highly overcast March day. The measure of performance was the maximum distance in feet from the Landolt C-ring at which the direction of the gap could be correctly identified. Admittedly, these data are quite limited, but of some interest to the current study are the trends in the findings comparing the naked eye with the 15% visor condition. Minimum distances at which the break in the ring could be detected are shown in Table 94. Of interest is the high degree of similarity among distances required on the clear morning as opposed to the trend associated with data collected during the overcast afternoon. In the latter condition, as visor transmitivity decreased, it was necessary to drive progressively closer to the C-ring in order to identify the location of the break in the ring. If these data show nothing else, they do indicate that the use of a sun visor may influence detection tasks, and that the influence may vary as a function of surround illumination level.

Finally, using a Snellen eye chart, Parker (Ref. 261) measured the visual acuity of four subjects using the three transmitivity visors in addition to the naked eye. Measures of acuity were highly comparable and frequently identical for the naked eye and using the 15% transmitivity visor. Marked decreases in acuity were found only for the 1% transmitivity visor.

The question remains, what are the impacts of the use of helmet-mounted visors or sun glasses upon symbol luminance requirements and, consequently, display contrast ratio requirements? No clear answer is available from the literature. However, there is evidence that the use of such devices may impact upon symbol luminance requirements. Unfortunately, practically none of the contrast ratio data which are available have taken this factor into account.

It is clear (Refs. 4 and 261) that the effects of visors transmitting between 10% and 15% of the illumination incident upon them vary as a function of ambient illumination level. At higher levels (e.g., 2,000 to 7,000 Ft. Lamberts) the use of such devices appears to have a minimal effect upon contrast discrimination or measures of visual acuity, although the latter factor is far from fully established. At lower ambient

Table 94. Mean** Distance in Feet at which Direction of Break in Landolt C-Ring could be Identified. (Adapted from Parker, Ref. 261)

	Helmet Mounted Visor Conditions			
	No Visor	15%*	3%	1%
Clear Morning	1,087	958	1,038	992
Overcast Afternoon	767	618	476	373

*Percent transmitivity of visor.
**Each mean based upon 15 measurements.

illumination levels (e.g., 500 to 700 Ft. Lamberts), however, the use of light attenuating devices appears to have a possibly negative impact upon acuity and may result in increased display reading times. Finally, King et al. (Ref. 208) have clearly shown that the effects which such devices have upon minimum legibility contrast ratios may vary as a function of display configuration. King et al. also have shown, however, that such effects may not be apparent when symbol luminance is increased above that minimally required for display legibility. This finding offers considerable promise. Assuming that engineering technology will develop means of achieving symbol luminance and contrast capabilities which will allow pilots to adjust symbol brightness levels above those minimally required for legibility, then it may make no difference whether or not the pilot is using a visor or sun glasses.

A requirement exists for additional research directed toward providing an understanding of the operational significance of the use of helmet-mounted visors and sun glasses upon symbol emitted luminance and contrast requirements. It is felt, however, that the research should be directed toward identifying whether eye adaptation level, filter bandwidth (color) or interactions of these with symbol color produce operationally meaningful effects. It also is felt that symbol luminances and, therefore, contrasts above those minimally needed to produce legibility should be employed. This follows, since it has long been recognized and again recently demonstrated (Ref. 208) that, given a choice, pilots will increase display emitted luminance and, therefore, also contrast above minimum legibility levels. King et al. also have shown that any effects of sun visors or sun glasses may be minimal or non-existent at these higher symbol luminance levels. Available data are quite limited, however, and before ignoring the effects of sun visors,

the effects reported by King et al. should at least be replicated. This is particularly true in light of the other data which exist.

The effects of eye adaptation levels ranging through 10,000 Ft. Lamberts and sun visors remain unresolved in terms of predicting symbol luminance and, therefore, contrast ratio requirements. Existing data generally relate to acuity tasks or unspecified tasks. No comprehensive data were found which would relate directly to display legibility tasks for comfortably bright and contrasty symbology. Thus, the display designer is confronted with the requirement to empirically demonstrate the adequacy of symbol luminance and contrast throughout the anticipated range of ambient illuminance levels. Contrast ratio requirements determined with no visor at the equivalent reduced display background luminance level will, however, provide an approximation of required contrast needed for conditions wherein pilots wear visors.

ILLUMINATION INCIDENT UPON DISPLAY FACES

Panel-Mounted Displays

The amount of illumination incident upon the display face and the reflectivity of display face materials are primary factors influencing display "washout". Through the use of anti-reflective display filters in conjunction with high brightness symbology, display washout may be overcome. It is necessary, however, to have a sound indication of the magnitude of the illumination incident upon the display in order to specify filter and symbol luminance and contrast requirements.

From a preceding discussion, it was concluded that the maximum direct illuminance of sunlight passing through a representative canopy is approximately 10,000 Ft. Candles. In a worst-case circumstance, therefore, approximately 10,000 Ft. Candles of illuminance could be incident upon the display face. This does not necessarily imply, however, that 10,000 Ft. Candles is representative of operationally experienced maximum incident illumination levels. This follows, since cockpit configuration and associated structural members of glare shields may serve to block some illumination. In this respect, it is desirable to review the literature which directly addresses the amount of illuminance which might realistically be expected to be incident upon electronic display surfaces.

Bruns and Miller (Ref. 51) report that the maximum noontime direct sunlight brightness reflected from a magnesium oxide surface located near the radar display in the rear seat of the F-4 aircraft was 7,500 Ft. Lamberts. The latitude and time of year at which the measurements were made were not specified.

Peterson (Ref. 263) has reported some limited panel illumination data which were measured at various headings relative to the sun. A "white reference standard" of unspecified reflectivity was mounted on the left side of the pilot's instrument panel in a KC-135 aircraft and on the right center of a T-39 aircraft instrument panel. Maximum luminance reflected from the white reflective surface was approximately 200 Ft. Lamberts. The measurements were made at 08:00 hours on 1 September at an altitude of 20,000 feet in the KC-135 and at 3:00 P.M. on 2 June at an altitude of 10,000 feet in the T-39. Measurements of the illuminance of the horizon varied from 1,500 to 5,000 Ft. Candles. All measurements were made over Dayton, Ohio. Addis et al. (Ref. 1) made photometric measurements of the luminance of a white reflection surface positioned at various locations in the instrument panel of a T-39 aircraft. Luminance data are summarized in Table 95. Addis et al. do not indicate the latitude, season or time of day at which the measurements were made.

Table 95. T-39 Instrument Panel Luminance Measurements. (From Addis et al. Ref. 1).

Location of White Reflective Surface on Instrument Panel	Type of Illumination	Measured Luminance in Ft. Lamberts
Panel Scan	Indirect	87 - 100
Lower Right	Indirect	100
Lower Right	Indirect Diffused by Clouds	387
Lower Right	Direct Sun	8,125

King et al. (Ref. 208) measured luminances of a magnesium oxide surface located on an unshielded instrument panel in a mockup of a fighter aircraft configuration cockpit. Measurements were made when the mockup canopy was uniformly illuminated to values of 500, 3,100 and 8,600 Ft. Lamberts. Corresponding luminances measured from the MgO surface were 150, 900 and 3,000 Ft. Lamberts respectively. Extrapolating from these measurements to estimate the luminance at the panel which would correspond with 10,000 Ft. Lamberts of canopy illumination (as might be encountered while flying near the top of clouds), it would be expected that panel luminance would be approximately 3,500 Ft. Lamberts for indirect luminance.

The illuminance incident upon electronic display faces is one of the key factors affecting the proper design of electronic flight displays. It is apparent from the foregoing discussion that data regarding this factor are relatively meager and fairly highly inconsistent. The inconsistencies, of course, do not imply irregularities in the manners in which the luminance measurements may have been made. Rather, the inconsistencies arise primarily from the relatively unknown impacts of total cockpit geometry (Ref. 206), variations in the type and level of illumination external to the cockpit and simply the relatively few measurements which have been made of illuminance incident upon instrument panels in a variety of operational aircraft and under a total spectrum of anticipated atmospheric conditions and times of day.

These considerations do not allow for a valid specification of the illumination conditions under which electronically generated displays must be designed to operate. If, however, one were to select ranges of illuminances which might have to be dealt with, it would appear that the maximum range of luminance produced in direct sunlight would be from 7,500 to 8,200 Ft. L., although this figure might also approach 10,000 Ft. L.

Projected Displays

The question of the level of illumination with which projected displays, such as head-up displays or helmet-mounted sights, may have to cope must be addressed somewhat differently. Assuming that it is unrealistic to attempt to read a head-up display when flying directly into the sun, the amount of illuminance falling on a projected display or the brightness background against which such a display would have to be read is a direct function of the luminance levels of areas in the field of view immediately ahead of the aircraft. In this regard, it is also only realistic to examine the types of mission uses of head-up displays. Two uses which have historically received the greatest attention are approach and landing and aerial combat. In an approach and landing context, it would appear that earth horizon brightnesses up to 5,000 Ft. Lamberts must be considered (Ref. 263). In aerial weapon delivery tasks, it would appear that average sky luminance of approximately 2,000 to 3,000 Ft. Lamberts may be experienced, as may luminances of 9,000 to 10,000 Ft. Lamberts for flight into the tops of clouds. It may also be anticipated that background luminances in excess of 3,000 Ft. Lamberts might be experienced while diving down toward (but not into) the top of cloud cover. Unfortunately, no photometric data were identified which would indicate the luminance of cloud cover when viewed at various attitudes and altitudes above the cloud cover.

Finally, it is estimated that viewing glass used for head-up display applications have transmitivity factors ranging from 80% to 90% (Ref. 339). Considering also that canopy light transmitivity

of approximately 90% also is involved, it follows that head-up display background luminance will be at approximately 81% of the exterior scene luminance in front of the display. Under what appears to be the worst-case condition, this would be 81% of 10,000 Ft. Lamberts, or approximately 8,000 Ft. Lamberts, based upon existing photometric data. It is recognized that this estimate may be low. Again, the need for additional description photometric measurements is apparent.

DISPLAY BACKGROUND LUMINANCE

Display background luminance level is a result of one or more of the following factors: ambient light reflected from the display face, spurious noise generated on the display face resulting fron noise in the signal or circuits and photoluminescence of display phosphors due to ambient light striking and exciting the phosphors. The use of filters and anti-reflective coatings on the display face can serve to reduce each of these effects, thus resulting in reduced display background luminance. Reductions in display background luminance, in turn, result in reductions in emitted symbol luminance needed to produce desired symbol-display contrast. Ignoring spurious visual noise and phosphor photoluminescence, the following factors may be considered as primarily affecting display background luminance, symbol luminance, symbol-display brightness contrast and symbol-display color contrast:

- Intensity and spectral bandwidth of illuminance incident upon the display.

- Type of filter used, if any (neutral density, thin film high contrast, circularly polarizing, micromesh, wire mesh, or trichroic).

- Filter transmitivity, reflectivity and bandwidth.

- Reflectance of display structure, including phosphor and surface materials.

- Display emission spectral bandwidth.

Filters are frequently used in conjunction with electronic displays. In the flight environment, it would appear that the use of filters or similar light absorbing techniques will be mandatory. The value of any display filtering technique depends upon the extent to which the filter can absorb (or block) illuminance incident upon the display face while transmitting luminance emitted by the display.

There appears to be wide misconception regarding the utility of using light absorbing filters over display faces. The misconception appears to involve the fact that any such filter

will reduce the observed luminance of display symbology. The misconception is that a reduction in symbol luminance is always undesirable. This is untrue. The objective of using filters is to enhance the contrast between symbology and display background luminances. Any filter which reduced display background luminance more than it reduces symbology luminances offers the potential for improving symbol/display contrast. Obviously, there are extremes beyond which the utility of filtering techniques produces negative returns. For example, as filter transmitivity approaches zero, requirements for emitted symbol luminance at the display surface might become so severe as to result in severely shortened display life, either because of phosphor burn in the case of CRT displays, or because of material failures in the case of solid state displays.

The lower limits of transmitivity and reflectance of filters may be considerably different from those which currently are envisioned as practical. Ketchel and Jenney (Ref. 206), for example, indicate that filters transmitting less than 70 percent would be useless for application to electroluminescent displays. King et al. (Ref. 208), on the other hand, used thin film high contrast filters which transmitted approximately 27%, and reflected 2.2% of the illuminance incident upon them, and were able to achieve "comfortably" bright electroluminescent display symbology even under conditions in which incident illuminance was 10,000 Ft. Candles. Subsequently, filters were developed and tested which transmitted approximately 10% and reflected only 0.3% of the illuminance incident upon them. Although transmitivity of the second generation filters was only one-third that of the first generation filters, they reflected only one-seventh as much incident illuminance. Consequently, contrast between symbology and background was enhanced, and less emitted luminance was required in order to produce "comfortably" bright symbology. Display life also was lengthened.

An approach to display design, particularly for cockpit applications, which does not consider the latest state-of-the-art in filter technology does not appear practical. Many of the derogatory comments directed toward the use of filters appear unwarranted, and the advantages which filters offer both in terms of legibility and display life are quite encouraging.

Filter Types

Rather little has been published regarding the utility or disadvantages of various types of filters for cockpit electronic display application. Even though concrete human performance data for various filtering techniques are extremely limited at this time, several filter techniques are discussed below.

Neutral density filters are transparencies which reduce the intensity of light transmission without significantly altering the spectral composition of the light. Neutral density filters

reduce display luminance as a function of their density and, therefore, transmitivity. They enhance contrast because illuminance incident upon the display face is attenuated once as it passes through the filter on its way to the display face and again on the return trip from the display face to the observer's eyes. Emitted luminance, however, passes through the filter only once. It has been pointed out, however, (Refs. 206 and 263) that neutral density filters are not highly efficient.

Thin film high-contrast filters work on the same fundamental principle as neutral density filters, but are designed to enhance absorption of illuminance. This is accomplished through the use of nonhomogeneous neutral density filtering material. Such filters absorb illuminance passing straight through the structure, but more important, they absorb light scattered from collisions with the nonhomogeneous material (Ref. 263). Nonhomogeneous high-contrast filters have been used extensively in research dealing with the legibility of electroluminescent displays under high ambient illumination conditions (e.g., Refs. 1, 208 and 265).

Circular polarizing filters incorporate a linearly polarizing filter plus a quarter-wave retardation sheet which has its axis oriented at 45 degrees to the transmission direction of the linear polarizer. This configuration 'twists' light so that vibrations leaving the retardation sheet form a helix of circularity. When circularly polarized light reflects from a spectral surface, the direction of rotation is reversed. On again passing through the retardation sheet, the change in direction and rotation results in transforming the reflected circular polarity into linear exit polarity, oriented 90 degrees from that created initially when the light first entered the filter. Since a linear polarizing filter does not efficiently transmit light 90 degrees off axis, the net result is a blocking of reflected ambient illumination, but a transmitting of display-emitted luminance. It has been pointed out (Ref. 206) that the blocking effect of the circular polarizing filter is most pronounced when the reflecting surface emits specular reflections. Because phosphors tend to emit both specular and nonspecular (depolarizing) reflections, the amount of ambient washout protection varies as a function of this factor. Utility of the circular polarizer, therefore, is most pronounced when specular reflections are involved (Ref. 84).

Micromesh filters are sometimes referred to as honeycomb, grid or directional filters. The filter is made up of finely perforated metal plates which are then laminated between layers of glass. The filter, thus, consists of thousands of small, transparent cells of selectable diameter and depth. Luminance

striking the filter parallel to the axis of the cells is passed; luminance striking at more oblique angles of incidence (generally plus or minus 15 degrees) is blocked. The incident angle at which light is passed is called the cone of acceptance and is determined by the diameter and depth of the light transmitting cells. As Ketchel and Jenney (Ref. 206) point out, the observer must keep his head within the cone of acceptance in order to be able to see displayed content. At a viewing distance of 28 inches, a plus or minus 15 degree cone would allow head movement of approximately plus or minus seven inches laterally or vertically from an axis normal to and passing through the center of the display. Similarly, however, illuminance incident upon the display face also must have its origin within the cone of acceptance in order to produce maximum display washout. The probability of this occurring is a function both of aircraft orientation relative to the sun or other source of illuminance and cockpit configuration, including bulkhead location and canopy dimensions. It would appear, particularly for single seat or tandem fighter cockpit configurations, that display washout might occur if the sun were located directly behind, but slightly above the longitudinal axis of the aircraft. Additionally, the cone of acceptance would preclude side-by-side crew sharing of displays, which could be a serious drawback for the use of micromesh filters in certain cockpit configurations. Also, considering multi-jet cargo, transport or bomber aircraft in which side-by-side crew seating is common practice, it would appear impractical to use micromesh filters over electronic displays of other than flight information since, for example, engine instruments are centrally located on such panels, and neither crewmember would be able to read the instruments without exaggerated lateral head and body movement.

Trichroic filters have been examined in relation to enhancing symbol contrast for head-up displays (Ref. 195). A trichroic coating is a thin film deposit which reflects a narrow wavelength band of visible energy (e.g., 50 millimicrons wide) (Ref. 206) while transmitting most of the visible energy at both longer and shorter wavelengths. The net result is an enhancement of color contrast for the particular color (wavelength) for which the coating is designed. As Ketchel and Jenney (Ref. 206) point out, when the filter notch is designed to remove the specific wavelengths of light which match the display phosphor color, a contrast enhancement occurs because the display color which is projected against the head-up display combining glass is reflected back, while little matching real-world color of the same wavelength band is present to compete with it. Additional discussion regarding the use of trichroic filters and the effects upon usage of color codes may be found in References 278 and 279.

Wire-mesh filters, not to be confused with micromesh filters, also have received some attention. Wire-mesh filters consist of strands of wire arranged into a cross-hatch pattern and embedded in a glass carrier. The carrier may be only partially transparent, as a neutral density filter, and may be coated with anti-reflective

coatings. Wire-mesh filters are designated by (a) the diameter of the wire used and (b) the number of wires and intervals per inch. Thus, a 2.1 mil 200 mesh filter has a wire diameter of 0.0021 inches with 100 wires and 100 spaces per inch.

Bruns and Miller (Ref. 51) explored the effects of three wire-mesh filters upon the measured contrasts of a ten-step gray scale of a TV monitor. The three filters were: a 2.5 mil 400 mesh experimental filter; a 2.1 mil 200 mesh Techtronic oscilloscope filter; and a 3 mil 325 mesh experimental filter. Transmitivities for the three filters were 21%, 27% and 25% respectively. The effects of the filters were examined by placing each filter over the TV monitor and making photometric measurements of the resulting luminance of each step in a standard TV test pattern gray scale. Only two levels of illuminance upon the display were used. They were 6.5 Ft. Lamberts and 2,000 Ft. Lamberts. Table 96 presents the data which resulted from the photometric measurements. Figure 194 summarizes the data converted to measures of percent contrast. It is apparent from the data presented that gray scale contrast was enhanced for the lighter gray steps, but was decreased for the darker gray steps. Bruns and Miller conclude that the 2.5 mil 400 mesh experimental filter was most effective in transmitting display luminance while reflecting and absorbing ambient illuminance. The 2.1 mil 200 mesh Techtronic oscilloscope filter was nearly as effective, while the 3 mil 325 mesh experimental filter proved to be somewhat poorer. The effects of the filters upon some index of human task performance were not examined.

Combinations of filters have received little apparent attention, but appear to offer promise. Colman et al. (Ref. 84) report the development of a compound filter for application in air traffic control tower radars. The filter incorporates the "invisible glass" principle which is covered by two basic patents: U.S. Patent No. 1,911,881 dated 30 May 1933 yo Gerald Brown of Barnes, London, England, and U.S. Patent No. 2,003,735 dated 4 June 1935 to Gerald Brown and Edward Pollard. Fundamentally, the "invisible glass" principle is based upon the law of reflection; i.e., the angle of incidence equals the angle of reflection. By curving a glass surface so that light incident to the surface is always reflected away from the eye of the observer and into a light absorbing surface (or light trap), numerous reflections can be eliminated. To further control illuminance reflected from the radar display face, Colman et al. arranged a circularly polarizing filter on the tube side of the "invisible glass". Although detailed data are not presented, Colman et al. indicate that comparative physical measurements were made which showed a reduction in reflected luminance of 97%. Limitations of this technique for cockpit application, however, appear to include the design of an extensive physical shield on either side of the display to support the filter as well as to block illuminance impinging upon the display face from the side.

Table 96. Measured Luminance Values (Ft. Lamberts) for Several Shades of Gray with 6.5 and 2,000 Ft. Lamberts of Ambient Light. (Adapted from Ref. 51)

Ambient Luminance of 6.5 Ft. Lamberts

	Gray Step	Open Monitor	Filter 2.1-Mil 200-Mesh	Filter 3.0-Mil 325-Mesh	Filter 2.5-Mil 400-Mesh
	1	.4	0.6	0.6	0.5
	2	6	1.0	1.0	0.7
	3	10	2.1	1.7	1.5
	4	16	3.4	3.1	2.6
Lighter	5	22	6.0	5.8	4.8
	6	42	13.0	11.0	8.4
	7	73	22.0	19.0	17.0
	8	123	30.0	28.0	22.0
↓	9	177	42.0	40.0	34.0
	10	230	58.0	54.0	42.0

Ambient Luminance of 2,000 Ft. Lamberts

	Gray Step	Open Monitor	Filter 2.1-Mil 200-Mesh	Filter 3.0-Mil 325-Mesh	Filter 2.5-Mil 400-Mesh
	1	890	95	105	68
	2	920	98	105	73
	3	945	99	103	75
	4	960	99	103	75
Lighter	5	980	99	110	78
	6	990	105	117	84
	7	1,010	118	128	95
	8	1.050	122	135	102
↓	9	1,110	136	156	106
	10	1,150	145	160	110

King et al. (Ref. 208) report limited data from a brief exploration which was intended to improve the contrast of symbols on electroluminescent displays. They found that adding a circularly polarizing filter to an existing thin film high-contrast filter reduced illuminance reflected from the displays from approximately 2.2% to 0.3%. The reduction in reflected luminance was accompanied by a reduction in emitted luminance necessary to produce legible displays.

Other contrast enhancing techniques also exist. One of the more promising is the transparent phosphor which will allow a high percentage of illuminance incident upon a display face to pass through the phosphor layer to the interior of the display where, with proper design, much of the transmitted illuminance may be absorbed (Ref. 111). The advantage of this technique lies in the fact that since less incident illuminance is reflected from the display surface, filters of higher transmitivities might

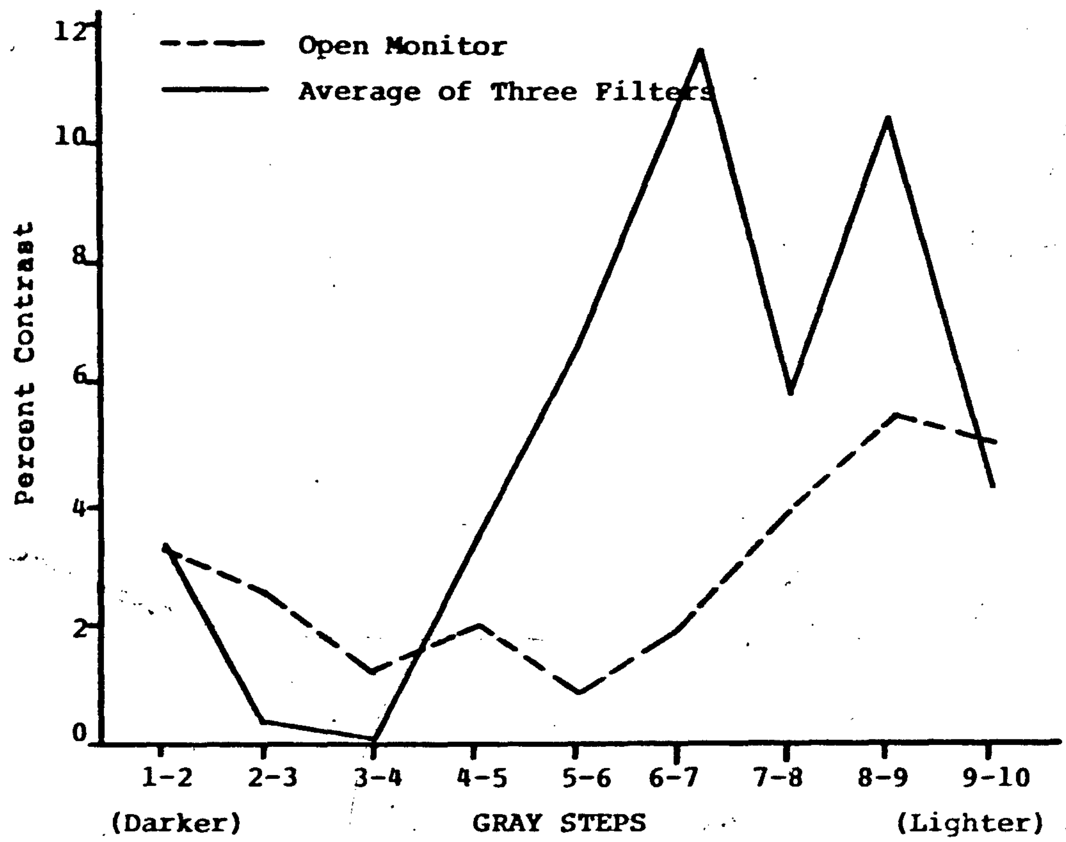


Figure 194. Comparison of Percent Contract Between Pairs of Adjacent Shades of Gray for Open Monitor Versus Average of Three Wire Mesh Filters Under High Ambient Lighting (2,000 Ft. Lamberts). (Adapted from Ref. 51)

be employed to reduce display background luminance levels without severely attenuating emitted luminance of symbology. Ketchel and Jenney (Ref. 206) also point to non-linear optical filters (Ref. 211) and fiber optic faceplates as potentially promising contrast enhancing techniques. At present, however, little is known of the operational advantages of these techniques in terms of human performance.

Finally, Ketchel and Jenney reported some optimism about the development of a high resolution (1,000 line) high brightness CRT which would emit 20,000 Ft. Lamberts of peak highlight brightness. Even if such a CRT were to be developed, it would appear that even such a brute force approach would require the use of some display face filtering since the reported (Ref. 343) absolute maximum upper limit of human tolerance for luminance is 16,000 Ft. Lamberts. Neither the requirement for, nor the desirability of such high emitted luminance levels has been established. Indeed, the present authors conclude that high luminance emissions on the order of 20,000 Ft. Lamberts provide a questionable solution to the display visibility problem. King et al. (Ref. 208), for example, were able to achieve "comfortably" bright electroluminescent displays with a maximum emitted luminance (behind a thin film high contrast filter) of less than 300 Ft. Lamberts. This was accomplished when 10,000 Ft. Candles of illuminance was incident upon the displays and was achieved through the control of both reflected and transmitted luminances by means of filter design. Although the findings of King et al. are limited to the bargraph and numeric readout displays which they studied, there certainly appears to be a clue here for other display applications, including radar, imagery and flight display presentations.

Conclusions

Because the human eye is ratio sensitive, it responds to luminance differences between symbology and general display background. Symbol-display contrast can be enhanced either by brute force methods of creating high symbol luminance, by using filtering or transparent phosphor techniques to reduce display background luminances, or by combinations of the two.

This brief review of types of filters and their potential utility for reducing display background luminance as a technique for enhancing symbol-display contrast was intended to identify some of the alternatives which currently exist. Obviously, it was not intended as a comprehensive state-of-the-art survey of filter design and filter technology. Physicists, astronomers, microscopists, photographers and others all make use of special types of filters. A review of their literature and techniques should prove valuable and useful to the display design engineer.

Requirements for human factors data involve the comprehensive specification of symbol-display contrast requirements for various types and colors of symbology, operator tasks and eye adaptation levels. A primary requirement for developing the necessary contrast data is the specification of the range of display background luminances which are to be anticipated for operational, airborne electronic displays. The utility of various filtering techniques has been demonstrated. Furthermore, the use of display face filtering or transparent phosphor techniques appears to offer the most promising avenue for future display design. Hence, the question is: What is the probable range of display background luminance levels which might be anticipated in filtered electronic displays designed for cockpit usage?

The use of filters has received some attention in the human factors literature. A review of this literature, however, identified no comprehensive data relating to the effects of various filter types, either singly or in combination with other display reflectance or emission characteristics. Quantitative data which were identified were not broad in scope, having been derived solely from highly specific research and development contexts. Unfortunately, no photometric data were identified which dealt specifically with some of the more promising developments such as transparent phosphor displays.

Based upon the human factors literature, Table 97 presents a representative summary of recent measurements of the combined effects of filters and other display characteristics upon display background luminance levels under high ambient cockpit light conditions. From such data it is difficult to objectively establish the range of display background luminances which may characterize cockpit applications of unshielded, panel-mounted electronic displays. The lower limit is relatively easy to anticipate at approximately 0.1 Ft. Lamberts. The upper limit, however, is more difficult to anticipate.

Based upon the data in Table 97, for conditions under which 10,000 Ft. Candles of illuminance would be incident upon a panel-mounted electronic flight display, resulting display background luminances could range from 30 to over 1,700 Ft. Lamberts, depending upon display construction and the type of filter used. Because the practicality of a display-filter combination resulting in only 0.3% reflectance has been demonstrated (Ref. 208), it is reasonable to assume that maximum background luminances for future displays should be closer to 30 Ft. Lamberts than to 1,700 Ft. Lamberts. The problem is to realistically identify a probable maximum background luminance from within this range. At this time, it is apparent that any decision is somewhat arbitrary. However, for panel-mounted displays incorporating a high degree of filtering, it is our judgement that background luminance levels in excess of 1,000 Ft. Lamberts can be avoided. It also is apparent that additional filter development activities are quite

Table 97. Measures of Reflected Display Luminance Under Conditions of High Illuminance Incident Upon Display Faces.

Source	Filter Type	Level of Illuminance Incident Upon Display Face	Reflected Luminance (Display Background)	Comments
Carel (Ref. 58)	None	10,000 Ft. C.	7,000 Ft. L.	Sunlight reflected from conventional TV phosphor and tube face.
King et. al. (Ref. 208)	Thin film high-contrast filter on EL display.	10,000 Ft. C.	220 Ft. L.	Luminance reflected from an electroluminescent bargraph display.
King et. al. (Ref. 208)	Thin film high-contrast filter and circular polarizer on EL display.	10,000 Ft. C.	30 Ft. L.	Luminance reflected from an electroluminescent bargraph display.
N.A.	50% transmitivity neutral density filter.	10,000 Ft. C.	1,750 Ft. L.	Computed value for a 50% transmitivity neutral density filter mounted in front of representative phosphor and tube face of 70% reflectance.

necessary, as are human factors evaluations of the utility of filters thus developed. A defensible selection of an upper limit for display background luminance would have to follow from such evaluations.

Obvious exceptions to the use of neutral density-type or mesh-type filters are head-up displays and the helmet-mounted displays. Each of these requires the maintenance of the pilot's ability to view real-world imagery and targets through the display faces. Based upon computations discussed previously, it is estimated that display background luminances for these types of displays from 0.1 to 8,000 Ft. Lamberts are to be anticipated. Thus the range of background luminance levels for panel-mounted displays lies well within the range of background luminance values which are to be anticipated for head-up displays.

The use of trichroic filtering techniques is finding wide application for head-up displays, and, consequently, both color and brightness contrast techniques are involved in making head-up display symbology legible under high ambient illumination conditions. Nonetheless, within the context of providing generalizable legibility contrast ratio design data which will be useful to the full spectrum of flight displays, it would appear quite reasonable to assume that this could be accomplished by establishing contrast ratios required to make various types of symbology legible against display background luminance levels ranging from 0.1 to 8,000 Ft. Lamberts. However, above 1,000 Ft. Lamberts, it would appear only reasonable to establish brightness contrast requirements only while also taking into consideration the color contrast provided by trichroic filtering techniques.

CONTRAST POLARITY

In a brief review of the literature dealing with electronic display legibility contrast ratio requirements, Ketchel (Ref. 203) cited data from an unpublished report by Kelly (Ref. 200) dealing with the polarity of symbology for electronic displays. Reportedly, Kelly investigated light symbols against a dark TV display background and dark symbols against a light TV display background. It was concluded that, for televised symbols, white characters on a dark background are more legible under low ambient illumination levels, but that dark symbols on a light background were found superior when ambient illumination level were on the order of 2,000 Ft. Lamberts. Ketchel further reported that high ambient illumination affected dark symbols differently than light symbols. A change in ambient illumination from 585 to 2,005 Ft. Lamberts caused a measured increase of 16 Ft. Lamberts in the luminance values of the dark symbols, but added 25 Ft. Lamberts to the lighter symbols. Presumably, the increases resulted from reflectance and photoluminescence.

If the latter measurements are correct, it would appear that a contradiction may exist in the above comments. The contradiction stems from the fact that Kelly reportedly indicated that, under higher ambient illumination levels, dark symbols on a light background were preferred. However, it is also reported that, as expected, greater illuminance values were associated with light symbols under the high ambient conditions. It would seem reasonable to expect, therefore, that light symbols on a dark background would be preferred for high ambient illumination conditions, since the higher ambients would produce greater increases in symbol luminance than in darker display background luminances, thereby enhancing the symbol-to-display background contrast. Ketchel, however, did not report the criteria upon which Kelly made his recommendations, and it is possible that a loss of symbol sharpness might have been associated with light symbols on a dark background.

In reviewing the literature dealing with the effects of direction of contrast upon alphanumeric legibility for televised displays, Shurtleff (Ref. 304) has concluded that direction of symbol contrast has a small effect upon alphanumeric legibility. Differences typically are on the order of 4% to 5% in reading error. Typically, overall reading errors associated with such studies have been quite large and on the order of 25% or greater. Consequently, a difference of 4% or 5% is of little practical significance. Shurtleff also points out, however, that data which are available are applicable primarily to display applications involving moderate to low ambient illumination levels, typically below 1,000 Ft. Lamberts.

Baker and Earl (Ref. 15) have reported a recent experimental study dealing with the detection, on a noise-free display, of small light radar pips against a darker display background versus darker pips against a light background. Relatively low display luminance were involved. They report no meaningful differences in visibility thresholds for the two directions of contrast.

From the available literature, it would appear that contrast polarity has little practical impact upon symbol identification. For conditions involving ambient illumination levels above 1,000 Ft. Lamberts and correspondingly high display background luminances, available experimental evidence indicates that dark symbols against a lighter background might result in improved legibility. As noted previously, however, one would anticipate that the opposite would prove to be the case because of considerations of display washout when a lighter display background is used. It would appear desirable, therefore, to briefly explore the effects of contrast polarity upon alphanumeric legibility and symbol identification under conditions of high ambient illuminance and higher display background luminances which might be anticipated in the cockpit. Although it would be anticipated that differences in legibility might be quite small, the fighter cockpit, for

example, provides a severe illumination environment for electronically generated displays, and there is little harm in attempting to maximize display legibility within that environment.

EMITTER COLOR

If electronic flight displays incorporate colored symbology, the specification of contrast ratios must take into account the fact that visual thresholds of the human eye vary as a function of the wavelength (color) of the symbol. Symbol-background color contrast also must be considered.

One attribute of single-frequency luminance which is related to its role as a color stimulus is wavelength. Wavelength is typically expressed in millimicrons (millionths of a millimeter). The shortest wavelength luminance which ordinarily is perceived as a color stimulus is 380 millimicrons, although under certain laboratory conditions luminance of wavelengths as short as 300 millimicrons may be visible. The longest wavelength luminance which ordinarily is perceived as a color stimulus is 770 millimicrons, although under carefully controlled conditions luminance of wavelengths as long as 1,000 millimicrons may be visible. For practical purposes, however, the human visible spectrum lies between 380 and 770 millimicrons. Table 98 presents some color names typically associated with luminance wavelengths in the visible spectrum.

Figures 195 and 196 show the differential sensitivity of the human eye to wavelengths comprising the visible spectrum. Of particular interest are the photopic (cone) vision curves since these curves relate the human color vision. Figure 196 is the luminosity curve for the "standard observer" according to the 1931 agreements of the International Commission on Illumination.

The luminosity curve in Figure 196 is of greater value in the area of identifying contrast ratios for electronic display design since it relates the sensitivity of the cones of the eye to various wavelength luminances, and expresses the differential sensitivity relative to the maximum visual sensitivity, which occurs at 555 millimicrons (green-yellow symbology). The generality of the curve is further enhanced by the fact that the human eye is approximately as sensitive to white luminance as it is to the green-yellow luminance (555 millimicrons).

Thus, more radiant energy (e.g., watts) is required to produce visually detectable stimuli for wavelengths lying near the ends of the visible spectrum. Practically all photometers, however, are calibrated for the luminosity curve of the standard observer. Consequently, what the human eye would see as "less bright" because of the wavelength of the symbology, the photometer also will "see" (i.e., measure) as less luminous. Because

Table 98. Some Typical Color Names Associated with Luminance Wavelengths Comprising the Visible Spectrum.

Wavelength Band	Typically Associated Color Name
380-470	Reddish Blue
470-475	Blue
475-480	Greenish Blue
480-485	Blue-Green
485-495	Bluish Green
495-535	Green
535-555	Yellowish Green
555-565	Green-Yellow
565-575	Greenish Yellow
575-580	Yellow
580-585	Reddish Yellow
585-595	Yellow-Red
595-770	Yellowish Red

of this, contrast ratio computations based upon measured symbol and background luminances need not take wavelength into account. Using luminance estimates calculated from physical energy values, however, would require taking the luminosity function into account.

Research which has addressed legibility contrast ratio requirements for electronically-generated symbology has not systematically taken emitter (and thus symbology) and display background colors into account. This has not posed problems for black and white displays. However, the operational use of color in CRT displays is not unforseeable, and many solid state displays inherently involve colored symbology.

Design-oriented color contrast data are conspicuously lacking in the literature. Several well established facts about color vision, however, point up the need for such data. For example, a change in the color of a background will modify the perceived color of the symbol. Yellow and violet stimuli (at equal measured luminances) are indistinguishable at small angular subtenses. Discriminability of both color difference and saturation (amount of color) is degraded at very low and very high levels of illumination. These and similar laboratory findings point to the need for design-oriented color contrast data.

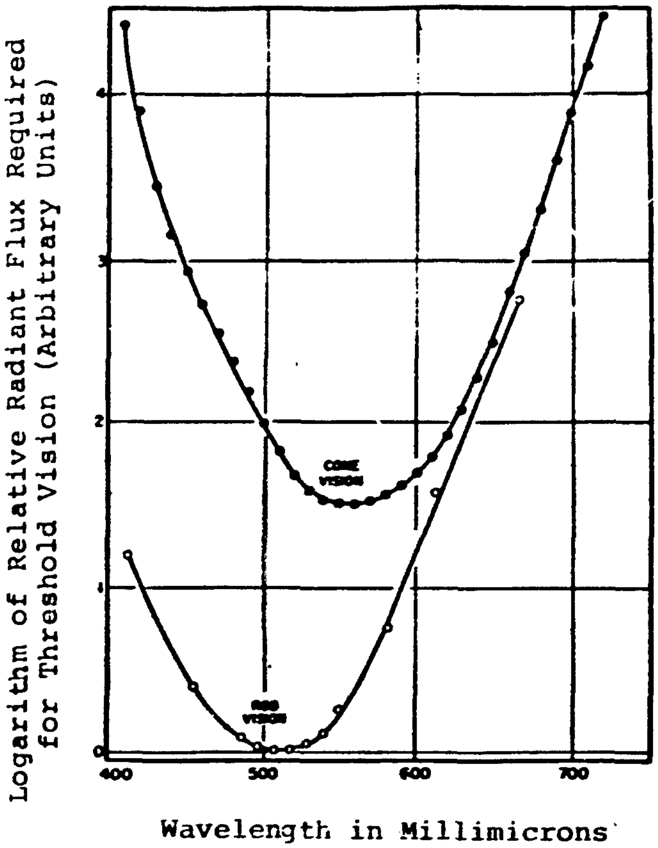


Figure 195. Relative Amounts of Radiant Flux Required to Stimulate Rods and Cones.

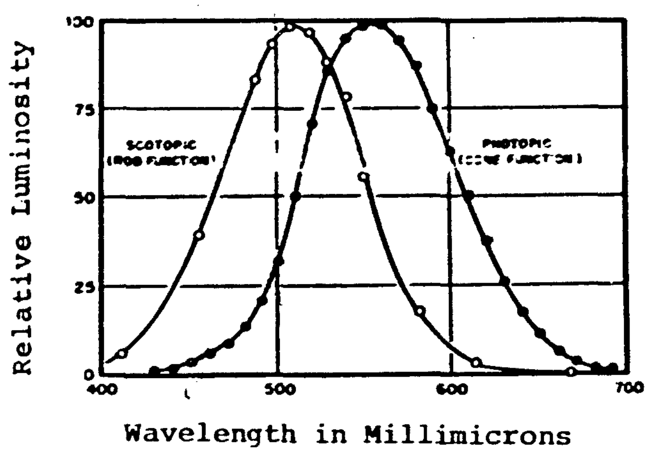


Figure 196. Photopic and Scotopic Relative Luminosity Curves.

The reader must be aware, therefore, that symbol-background color contrast is a significant design variable and that he must exercise his own variety of caution in specifying legibility contrast ratios for symbology of other than white or green-yellow color viewed against gray backgrounds since it is these wavelengths and wavelength combinations upon which the majority of design-oriented contrast ratio data have been taken.

EARLY CONTRAST RATIO RECOMMENDATIONS

In a 1961 report (Ref. 131), the General Electric Company suggested that a symbol-to-display background contrast ratio of 85% would result in good symbol visibility. The recommendation was made in conjunction with development of a contact analog display format. The recommendation, however, was not substantiated in any detail. Ketchel (Ref. 233) points out that the 85% figure may have been derived from data presented by Chapanis in Human Factors in Undersea Warfare (Ref. 260). In the book, Chapanis cited prior work by Connor and Ganoug (Ref. 86, and Cobb and Moss (Ref. 75). These data, although somewhat inconsistent, tended to show improvements in visual acuity between percent contrasts of 76 and 93% at a background luminance of 1.0 Ft. Lamberts, and between 50 and 100% contrasts at a background luminance of 100 Ft. Lamberts. A midpoint for these ranges would be approximately 85%. The limiting factor associated with these data is that they are based upon visual acuity tasks, and the correspondence to flight display tasks is not established. Finally, the range of display background luminances investigated may not be representative of those to be found in the cockpit, and varying eye adaptation levels and sun visor conditions are, of course, not reflected in the data.

COMPUTATIONS OF CONTRAST RATIOS

Carel (Ref. 58) has published a computational procedure for estimating symbol/display contrast requirements based upon contrast threshold data for the human eye published by Blackwell (Ref. 32). Carel indicates that given the ambient luminance and requirements for a given number of shades of gray, the dynamic range (ratio of least to greatest emitted luminance) and luminance requirements may be reasonably estimated for achromatic (black and white) displays. The procedure is based upon the premise that data are available which allow estimates of:

a) values required to reach a 50% threshold of visibility

b) values required to reach greater than 50% thresholds

c) values required to reach operationally useful image

d) values required to compensate for the fact that the eye may be adapted to luminance levels greater than those of the display

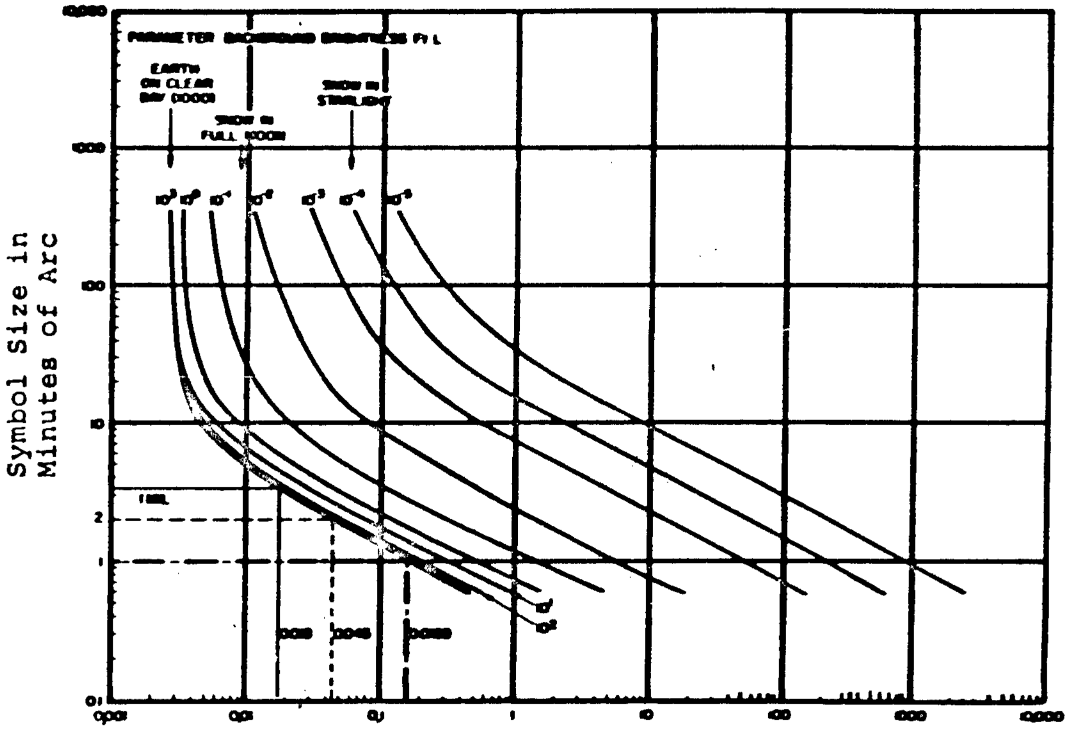
e) values required for achieving clearly discriminable gray shades.

By judicious use of existing data, estimates of required luminances and contrasts may be reached.

The basic data for all estimates were generated by Blackwell in his study (Ref. 32) of contrast thresholds of the human eye. The curves in Figure 197 are plotted from Blackwell's data and have been adapted from Carel. The curves show the contrast required for small stimuli to be visible 50% of the time. The curves are a function of background luminance and target size. Contrast ratios required for 99% threshold are estimated by first establishing the contrast required for 50% threshold for the target size and display background brightness of interest, and then multiplying the contrast ratio by three.

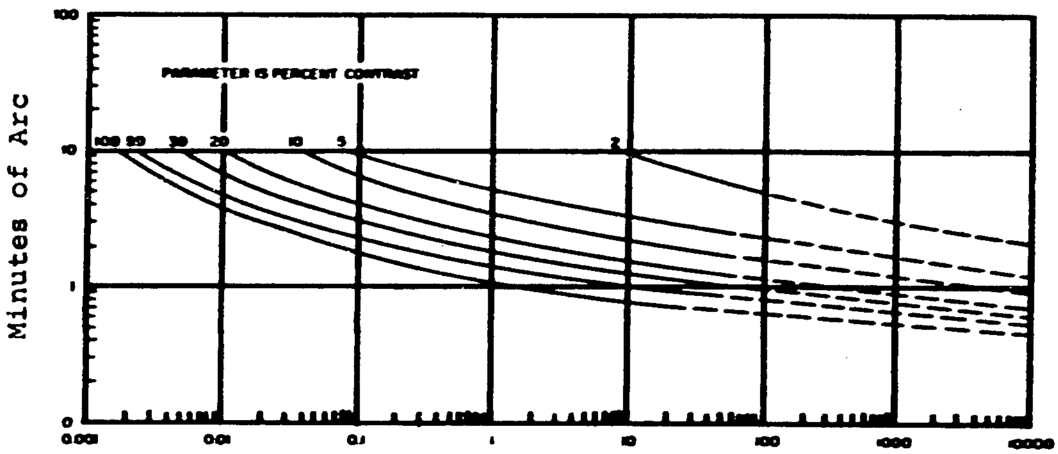
Figure 198, also adapted from Carel, shows how visual acuity also is affected by contrast and display background luminance. In a skeletal display, such as a VSD or HUD, requirements are not only that thin line elements comprising the symbology be usable, but also that readout accuracy be maintained by assuring that the separation between two elements be visually resolvable, at least down to separations equal to one line width. For this reason, the contrast ratios derived separately from Figure 197 and 198 should be compared, and in calculating display luminance requirements the most demanding value should be used. Contrast ratios determined from the figures also are multiplied by three in order to correct 50% thresholds, upon which the data are based, to 99% threshold of detection. A note of caution must be inserted. It is apparent in Figure 198 that data applicable to anticipated display background luminance (i.e., 30 to 1,700 Ft. L.) consist of extrapolations of curves generated for much lower background luminances.

The background luminance of a skeletal display, such as a VSD or HUD, may be considered as the brightness of the tube face where there is no image. Since the level of display background luminance may be considerably less than the surrounding (e.g., sky) luminance to which the eye is more adapted, the resulting "adaptation mismatch" may impact upon contrast ratio requirements. Carel indicates that the mismatch is of little practical consequence as long as the surround luminance level is no greater than ten times the display background luminance. For ratios greater than ten, Figure 199 is used in order to determine a



Contrast $\frac{\text{Symbol Luminance - Background Luminance}}{\text{Background Luminance}}$

Figure 197. Contrast Thresholds of the Eye.
(Adapted from Ref. 58)



Background Luminance in Ft. Lamberts

Figure 198. Visual Acuity as a Function of Contrast.
(Adapted from Ref. 58)

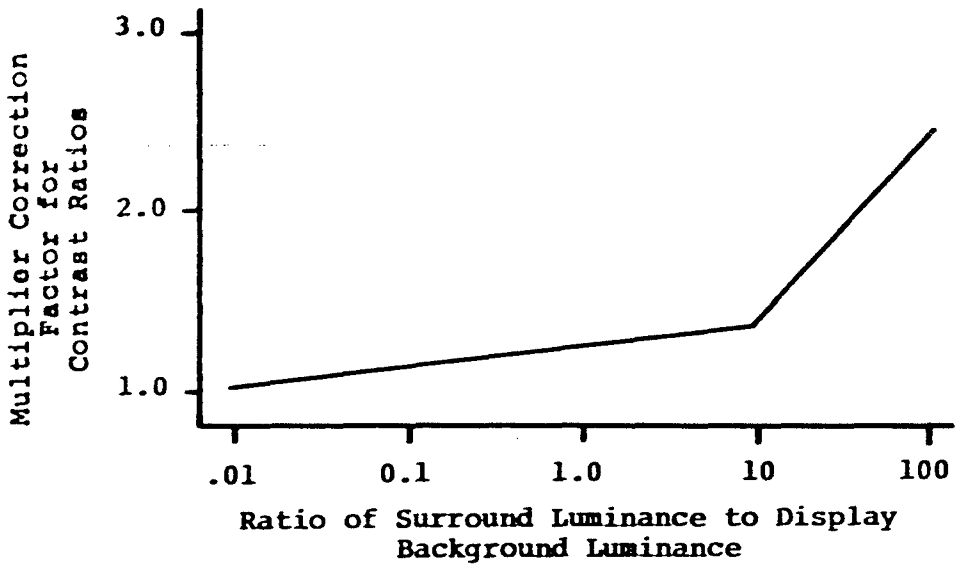


Figure 199. Correction Factors for Eye Adapation Mismatch. (Adapted from Carel, Ref. 58)

correction factor for the contrast ratios. It should be noted that the curve in Figure 199 is in close, although not total agreement with similar data shown in Figure 193.

Carel also indicates that correcting the basic Blackwell data or Chapanis data for both threshold and adaptation mismatch will result in a "ghostly" image. He indicates that resulting contrast ratios must be multiplied by at least five (Muller's constant) before the image will be bright enough to be viewed comfortably.

The result of the preceding computations is the contrast ratio required to make a target of specified minimum dimension clearly visible against a known display background brightness and for an estimated range of eye adaptation levels. Carel indicates that computations made in this manner are in good agreement with observations which he has made while informally investigating contrast requirements for useful shades of gray in cathode ray tubes.

A computational example follows in order to clarify Carel's procedure. Assume the following conditions: Lines used for display symbol construction are 3.4 minutes of arc in width. Display background luminance is 20 Ft. Lamberts; surround (sky) luminance is 200 Ft. L. From Figure 197, required contrast for 50% threshold for a 3.4 minute of arc target against a 20 Ft. Lambert background is 0.03 (note that these are not "percent

contrast" data). Figure 198 shows that the contrast required for that order of acuity is 0.05. The more stringent value of 0.05 is selected. The selected contrast ratio is multiplied by 3.0 to correct for 50% threshold, resulting in a contrast ratio of 0.15. Muller's constant (5) is applied, raising the contrast ratio to 0.75. Because of the difference in luminance between the surround and the display background, Figure 199 is consulted, and an "adaptation mismatch" correction factor of 1.2 is applied, raising the required contrast to its final value of 0.90. Using the following equation, the luminance of the symbology may be determined:

$$\text{Contrast} = \frac{\text{Symbol Luminance(S) - Background Luminance (B)}}{\text{Background Luminance (B)}} = 0.90$$

Since Symbol Luminance = Background Luminance + Emitted Luminance (E)

$$\text{Therefore, Contrast} = \frac{(B + E) - B}{B} = 0.90$$

$$= \frac{E}{B} = 0.90$$

$$= \frac{E}{20} = 0.90$$

Emitted luminance, thus, is 18 Ft. L.

Thus, under the conditions of this example, the display would be required to produce 18 Ft. Lamberts of symbol luminance over and above the 20 Ft. Lamberts of display background luminance (for a total, measured symbol luminance of 38 Ft. L.) in order to produce a "sufficiently contrasty" displayed image.

Carel also has used the above computational method for determining the luminance steps necessary to produce distinguishable gray scale steps. In determining gray scale steps, assume that, by virtue of the number of different symbols used on a VSD display, each symbol must be either discriminably brighter or less luminous than any other symbol.

Based upon the computational example used above, the symbol luminance was computed as 38 Ft. Lamberts as measured on the display face. The display background luminance was 20 Ft. L. Thus, two steps currently exist in the dynamic range of shades of gray. Assuming that additional display elements must be viewed against the 38 Ft. L. symbols, and remembering that a constrast ratio of 0.90 must obtain, then it follows that the next brightness step would have to be 72 Ft. L. (i.e., 38 + .9 x 38 = 72). Additional calculations are made in keeping with established requirements for "X" number of steps in the gray scale.

Three items merit attention at this point. First, Carel indicates that he has found that a 2:1 contrast is needed for pleasing and easily discriminable gray shades when displays are viewed under ambient luminances of 50 to 3,000 Ft. Lamberts. This corresponds with $\frac{S - B}{B.} = 1$. He does not indicate, however, whether this range of luminances was indicative of room luminance, only a portion of which would comprise display background luminance, or whether the range reflects display background luminances. It is felt that the former was probably the occasion, in which case eye "adaptation mismatch" might have been the significant contributing factor.

Second, it must be noted that the amount of luminance required for symbol discriminability is a positive power function of the number of steps required within a gray scale, at least in so far as VSD or HUD type symbology and displays are concerned.

Finally, there is no contention, either on the part of Carel or the present authors, that the computational procedure presented above can be indiscriminately applied directly to imagery types of displays such as photographs or side-looking radar imagery. Within the purvues of this study, the literature dealing with direct view displays uncovered no data relating display contrast or shades of gray to probability of target detection or recognition. No attempt is made here to imply that the above computational procedure either may or may not apply to complex imagery display formats.

RESEARCH ON CONTRAST RATIOS

The procedure presented above for computing legibility contrast ratios make several assumptions. It assumes that the type of symbology to which the procedure is applied is of little practical consequence. Experimental evidence cited on following pages makes this assumption questionable. Contrast ratios determined by computation are determined independent of task-related performance criteria and provide no assurances of producing necessary contrast for known or estimated task requirements, including measures of both speed and accuracy of response. Finally, the computations are based upon data obtained with the context of basic psychological research, and quantitative applications of basic laboratory research to applied problems are notoriously questionable.

It is necessary to have a good indication of contrast ratio requirements not only for worst-case, 10,000 Ft. Lambert ambient illumination environments, but also for the less demanding environmental illumination conditions where most of flying is done. One must ask what the applied experimental literature has provided which may be superior to analytic computational procedures

in this respect. The answer is that little has been provided. Early studies of target or symbol contrast requirements dealt extensively with radar room environments which are characterized by extremely low ambient illumination levels, at least in relation to those which may be experienced during flight. Also, practically none of the studies present the type of information necessary for generalizing to other settings. These data, therefore, are of little or no value.

Only within the past six years have generalizable, task-oriented data have become available. This is because of the only recent emphasis upon the development of techniques to make electronically generated displays legible in the cockpit without extensive physical shielding of the display faces. However, not all of the recent electronic display research has produced the type of data necessary to allow for the integration of findings of various investigators in order to identify trends. The generalizable data which are available are discussed below.

Panel-Mounted Displays

Ketchel (Ref. 203 and 204) has reported a study addressing the effects of eye adaptation upon symbol-display contrast ratio requirements for an operational electronic vertical situation display (Kaiser Direct View Indicator). Although the studies do not directly address symbol contrast requirements for easy legibility under high ambient illumination levels, they do provide data regarding the effects of the use of a helmet-mounted sun visor, display clutter, symbol size and symbol brightness and contrast upon the time required to locate and identify symbols of the type currently used in some electronic flight displays.

In Ketchel's study, the electronic display was located on a panel in a larger physical structure. A luminous surface, used in adapting participants eyes to various levels, was located above the display. For the portion of the study reported here, 24 subjects participated, with three having been assigned to each of eight experimental groups. All participants had 20/20 uncorrected vision and normal color vision.

The Kaiser Direct View Indicator incorporates a P-31 phosphor, producing green symbology with a spectral peak at 520 millimicrons. This is quite close to the photopic vision peak of the standard observer's eye (555 millimicrons). A micromesh filter was an integral part of the display. The display face measured 7.25 inches by 5.5 inches. The light adapting screen located above the electronic display measured 15 by 20 inches.

Two symbol shapes and sizes were used. One symbol was an inverted "T", and the other was a square. The maximum dimension of each symbol was 23 minutes of arc. Other symbol dimensions, such as stroke width, were not given.

All conditions were run both with participants wearing a 7.8% transmitivity visor and with participants wearing no protective visor. Two conditions of "display clutter" were investigated. Under that no-clutter condition, only the test symbols appeared on the display face. For clutter conditions, clutter consisted of 26 symbol elements, some made of black tape to simulate display fiducial marks, while others were electronically generated symbols of unspecified type and kind. The clutter condition was used to ascertain the effects of the presence of other flight display-like symbology on location and recognition times.

Two eye adapting luminances (5,000 and 10,000 Ft. Lamberts) were explored. A secondary task was used to ensure that participants were fixating upon the adapting screen during the eye adaptation periods.

Results from Ketchel's study are somewhat limited in their application to identifying display legibility contrast ratio requirements under high ambient illumination levels. This follows since the general display background luminance was only 3.2 Ft. Lamberts for the 5,000 Ft. Lambert adapting condition, and only 4.3 Ft. Lamberts for the 10,000 Ft. Lambert adapting condition. These levels of display background luminance are considerably below the maximum levels which might be anticipated with higher illuminances directly incident upon the display face. This is of particular importance since it is well established (Ref. 32 and 208) that legibility contrast ratio requirements vary as a function of display background luminance. Lower background luminances require less symbol luminance, but higher symbol contrast ratios in order to produce legibility. Finally, only three subjects were used in each experimental group.

Results of Ketchel's study are summarized in Figure 200. The latency times plotted in the figure are the times required by study participants to locate and identify the test symbols on the display and to depress a response button, minus the time required to depress the response button. Hence, latency times are location and identification times.

Several trends in Figure 200 are of interest. First, display "clutter" had statistically significant impact upon latency times only for the lower symbol luminance conditions. The finding is unexpectedly confusing, however, in that "clutter" produced both some of the shortest and the longest latencies. Of particular interest is the fact that latency times for all conditions could be driven to zero by adequate symbol luminance (and consequently symbol-display contrast). Finally, complex interactive effects were eliminated when symbol luminance and, therefore, symbol-display contrasts, exceeded minimum requirements for legibility. A similar trend will be shown subsequently in data by King et al. (Ref. 208).

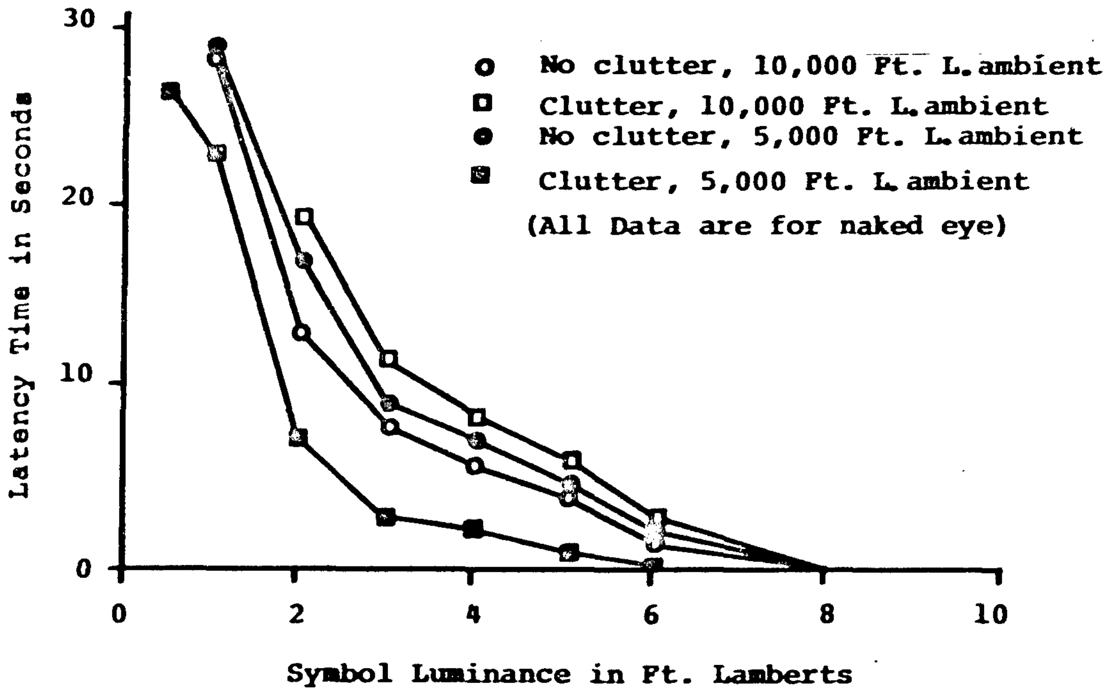


Figure 200. Display Reading Latency as a Function of Symbol Luminance and Display Clutter. (Adapted from Ketchel, Refs. 203 and 204)

Ketchel also has reported data which were derived by asking study participants to select what they judged were comfortable-to-use symbol luminances. These data are presented in Table 99. In order to provide a comparison for data in Table 99, a computation of percent contrast associated with the eight Ft. Lambert symbol brightness, shown in Figure 200 to minimize response latencies, results in a contrast ratio of 105% based upon the lowest display background luminance of 3.2 Ft. Lamberts. Of particular interest is the observation that subjectively comfortable contrast ratios are consistently and sizably above 105%, with the greatest deviations being generally associated with the 10,000 Ft. Lambert adaptation levels and with the non-visor conditions. This trend, however, is not totally consistent across all conditions.

Much of the relevant display contrast ratio research which has been published has been accomplished within the framework of designing electroluminescent displays for legibility under high ambient illumination conditions.

Petertyl et al. (Ref. 265) have reported some limited data generated in a study of electroluminescent (EL) display legibility requirements. Unfortunately, direct photometric measurements of EL emitted luminance were not made, nor were direct measurements

Table 99. Minimum Comfortable-to-Use Luminance and Percent Contrast Data. (Adapted from Ketchel, Ref. 203)

Groups Adapted to 10,000 Ft. Lambert	Group Mean Values		
	Symbol Luminance in Ft. L.	Display Background Luminance in Ft. L.	Percent Contrast
NV, U	15.7	3.6	336
V, U	21.1	7.3	189
NV, C	15.0	3.5	328
V, C	15.9	2.8	467
Mean	16.9	4.3	293
Groups Adapted to 5,000 Ft. Lambert			
NV, U	6.5	2.7	511
V, U	6.0	1.1	445
NV, C	5.1	2.0	155
V, C	23.4	6.9	239
Mean	10.3	3.2	221

Conditions: NV = No Visor; V = With Visor; U = Uncluttered Display; C = Cluttered Display

of display background luminance. All values were derived in an unspecified manner from either display excitation curves or from measures of the lumiance of a magnesium oxide surface located near the displays. Their data imply that reflectance coefficients of the displays varied over time. Accordingly, caution must be exercised in interpreting the data. The admonishment is further warranted because they do not indicate the human performance criterion which was used in determining acceptable display luminance and contrast.

The data in Table 100 were adapted from Petertyl et al. and reflect only those data collected with their "improved high-contrast display". They report that the display transmitted approximately 30% of the EL-generate emitted luminance and was characterized by about 5.0% diffuse reflectance and about 0.5% specular reflectance. Subjects' tasks apparently involved reading random five-digit numbers generated using seven-segment EL numerics. Other dimensions of the display were not given. Data were collected under several experimental illumination conditions. The illumination environment consisted of a simulated canopy windscreen which could be backlighted to produce an eye adaptation luminance source up to 5,300 Ft. Lamberts. Additionally, over-the-shoulder flood lighting could be applied to produce measured luminances at the instrument panel up to 1,350 Ft. Lamberts.

By far the most comprehensive legibility contrast ratio data have been published by King, et al. (Ref. 208). They also present contrast ratio data for "comfortably bright" displays. The data reflect a broad spectrum of cockpit illumination conditions, ranging from total darkness up to 10,000 Ft. Candles of illuminance directly incident upon the display face, and include conditions of lesser direct luminance but with 5,000 and 10,000 Ft. Lambert general sky luminances simulated.

The device used by King et al. consisted of a single-seat fighter cockpit mockup. The instrument panel was located 28 inches from the participants' eyes and incorporated no glare shield or other light shielding or blocking devices. Two displays were used. The three-digit numeric readout was made up of three matrices of seven EL segments each. Numeric height was 0.4 inches; width was 0.28 inches. Stroke width for each segment was 0.05 inches. The bargraph display was made up of 125 EL segments. Height of the bargraph was 5.0 inches; width was 0.25 inches. Each segment of the bargraph had a stroke width of 0.035 inches. Gaps between segments were 0.005 inches. The bar-graph was read against a scale which ranged from zero through 6.25 units with graduation marks at each 0.25 units. Each scale unit was the equivalent of five EL segments. Instrument bezels and the instrument panel were painted flat black.

Table 100. Median Legibility Contrast Ratios Required for High Contrast Electroluminescent Alphanumerics Legibility. (Adapted from Petertyl et al., Ref. 265)

	Windscreen Intensity (Ft. L.)	Intensity at M_gO Surface On Panel (Ft. L.)	Display Background Luminance (Ft. L.)	Display Emitted Luminance (Ft. L.)	Percent Contrast
Condition I					
2 Photofloods Windscreen Fluorescent Ceiling Luminance Overhead Fluorescents	5,000 to 5,300	1,350	72.0	1.31	1.8
Condition II					
Same as Condition I, minus 2 Photofloods	2,000 to 3,700	105	6.3	.12	1.9
Condition III					
Same as Condition II, minus Windscreen Fluorescents	12 to 20, Hotspot 49	49	2.6	.05	1.9
Condition IV					
Same as Condition III, minus Ceiling Luminance	4 to 22, Hotspot 49	18	1.5	.015	1.0

Two cockpit illumination sources were used. To simulate direct sunlight glare, a Xenon arc lamp shined over the participant's right shoulder onto the instrument panel. This was referred to as the incident illumination source, and levels of incident illumination were zero, 500, 5,000 and 10,000 Ft. Candles as measured using a magnesium oxide surface between the two EL displays. Surround (general canopy) illumination was provided by a bank of 21 400-watt Westinghouse type BOC metal halide lamps mounted in individual reflectors. Illuminance from the bank of lamps was diffused by two layers of sandblasted plastic, the inner most of which was the cockpit canopy. Luminance levels produced using the surround illumination system were zero, 500, 3,200 and 8,600 Ft. Lamberts of canopy luminance as measured from the participant's eye position. Table 101 presents display background luminances for each of the experimental conditions. As the two higher luminances, legibility and comfort-level contrast ratio data were collected both with and without a helmet-mounted sun visor of 11% transmitivity.

Thirty males, twenty of whom were USAF F-106 pilots, participated in the study. Fifteen received the incident illumination conditions and 15 received the surround illumination conditions.

The data collection procedure was as follows: After preliminary briefings, each participant was allowed approximately 20 minutes to dark adapt in the cockpit mockup. During this time, reading the bargraph and the numeric readout were practiced. Following adaptation, which included periodic checks on adaptation level, display luminance was progressively increased until either display could be read correctly three times in a row. Then display luminance was further increased until the participant reported that the display was "comfortably" bright. This procedure was followed separately for the numeric readout and the bargraph. The entire task procedure was then repeated in order to provide an experimental replication. Photometric measurements were made of display background luminance and activated display element luminance at each criterion point by focusing a photometer on a single EL segment. The task sequence was then repeated for each successively brighter cockpit luminance condition.

Legibility threshold data are shown in Table 101 for conditions in which the helmet-mounted sun visor was not used. Figure 201 presents emitted symbol luminance required for 99% probability of correct display reading (mean plus three standard deviations).

Several important trends are apparent in Figure 201. First, the separate curves for numeric readout and bargraph displays are comprised of data from both the incident and surround illumination conditions used by King et al. Consequently, the data points are comprised of conditions under which eye adaptation level did not correlate perfectly with display background luminance. For example, the higher display background luminances were produced

Table 101. Electroluminescent Display Legibility
Luminance Data for Bargraph and Numeric Readout Displays.
(Adapted from King et al., Ref. 208)

	BARGRAPH				NUMERIC			
Incident Illuminance	0	500	5,000	10,000	0	500	5,000	10,000
Display Background Luminance	0	11.8	114.1	197.0	0	10.4	103.C	181.2
Mean Symbol Luminance	.006	1.1	6.1	8.7	.065	3.7	21.5	30.1
Mean Plus 3 Standard Deviations, Symbol Luminance	.024	2.6	13.0	17.4	.104	8.5	55.7	64.9
Mean Percent Contrast	-	9.3	5.5	4.4	-	36.3	20.6	16.5
Mean Plus 3 Standard Deviations Pct. Contrast	-	21.9	10.9	9.5	-	86.7	53.9	33.0

	BARGRAPH				NUMERIC			
Surround Luminance	0	518	3,165	8,617	0	518	3,165	8,617
Display Background Luminance	0	11.8	57.1	148.8	0	4.0	21.1	58.2
Mean Symbol Luminance	.005	0.6	3.8	6.7	.009	1.6	6.7	14.0
Mean Plus 3 Standard Deviations, Symbol Luminance	.008	1.5	8.6	12.1	.015	3.1	13.9	29.6
Mean Percent Contrast	-	6.4	8.1	5.6	-	40.2	31.9	24.5
Mean Plus 3 Standard Deviations, Pct. Contrast	-	20.8	25.2	15.5	-	78.0	67.3	53.0

Note: All Luminance Values are in Ft. Lamberts.

Note: Symbol Luminances are Emitted Luminances only; i.e., Total Symbol Luminance (emitted plus reflected) minus Reflected Luminance

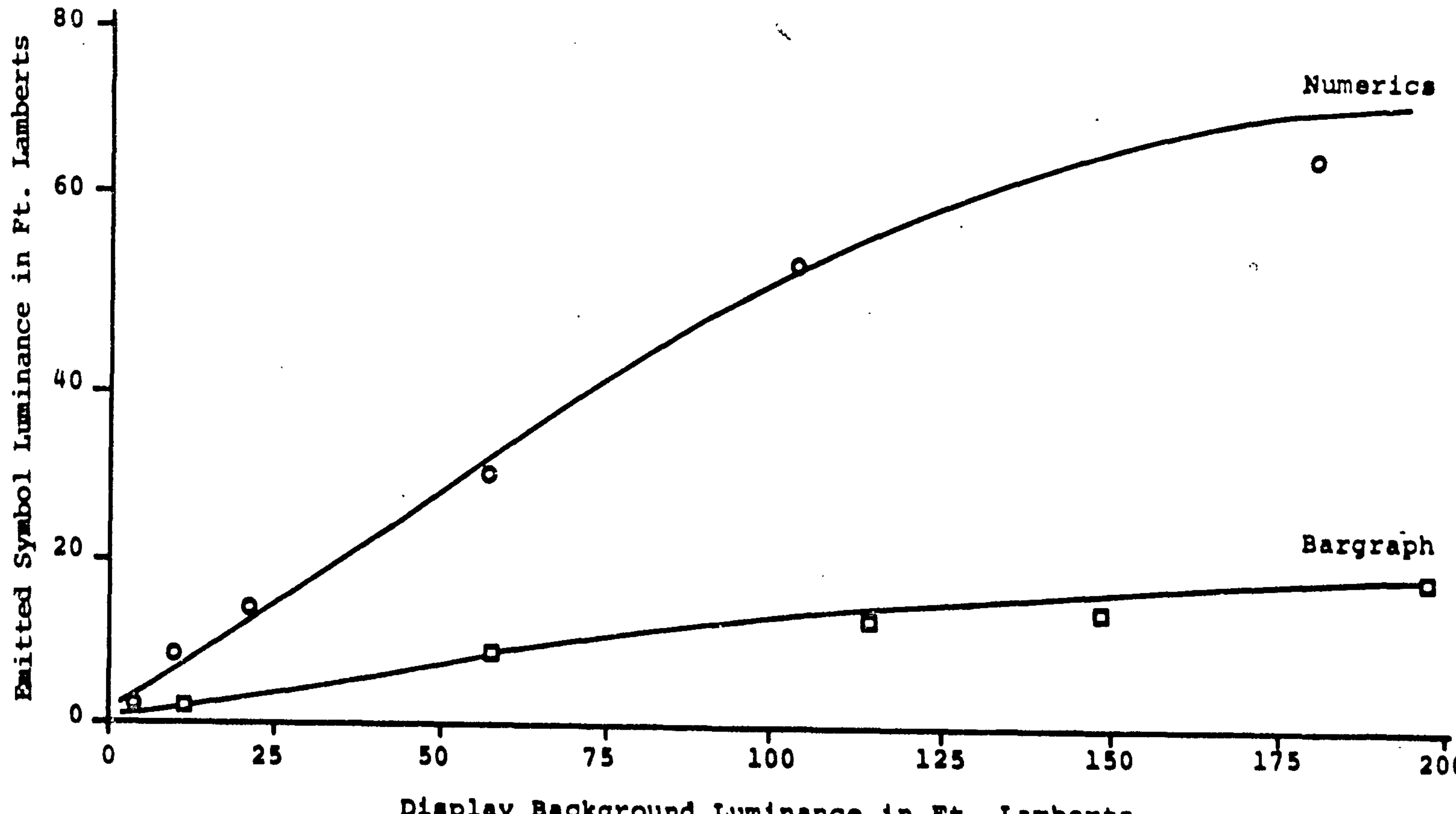


Figure 201. Emitted Symbol Luminance Required for 99% Display Legibility. (Based upon data from King et al., Ref. 208)

by direct incident flooding of the displays, while the higher eye adaptation levels occurred under conditions of higher general canopy surround illumination. It is of considerable interest to note that, in spite of this, the data points arrange themselves very nicely as a function of display background luminance. This indicates that the effects of display background luminance level are of considerably greater significance than eye adaptation level in determining emitted symbol luminance required to produce consistent display legibility.

A comparison of the two curves in Figure 201 also resulted in the observation that emitted luminance required for numeric readout legibility at selected display background luminance can be determined by identifying the emitted luminance for bargraph display legibility at that background luminance, and multiplying the bargraph luminance value by a factor of 3.8. In other words, the curve for the numeric readout is a multiplicative constant function of the curve for the bargraph display. The converse, of course, also holds true. The importance of this observation is that it implies that a baseline curve relating emitted symbol luminance to display background luminance for one particular display may be generalizable to other display formats if the necessary multiplicative constants, are known. Thus, legibility requirements could be predicted from a single equation and a table of constants rather than from complex sets of curves empirically determined for each display type and application.

Figure 202 presents the same data expressed as percent contrast. Examination of the figure shows that the relationships apparent in Figure 201 are not nearly as apparent. This is probably due to the fact that display background luminance is taken into account twice in Figure 202, once as the abscissa, and again as the denominator of the contrast ratio equation. The net result is an apparent bias of trends in the data.

Table 102 presents data from King et al. for ambient illumination conditions in which subjects wore a helmet-mounted visor of 11% transmitivity. Examination of the table shows that use of the visor had no practical impact upon contrast ratios or emitted luminances required for 99% bargraph legibility. The effect of the visor was almost minimal for the numeric readout under incident (simulated direct over-the-shoulder sunlight) conditions, but did produce a noticable influence under the surround (simulated general canopy) conditions. When background and symbol luminances are reduced to 11% of the tabled values to take effects of visor attenuation into account, the values do not fall neatly onto the curves of either Figure 201 or 202. Thus it continues to appear that the use of visors interacts with display type. The visor effects might include changing eye adaptation level, changing color contrast, or surface reflections on the visor itself. Data from King et al. do not provide a clear answer. However, since the primary results of wearing a visor

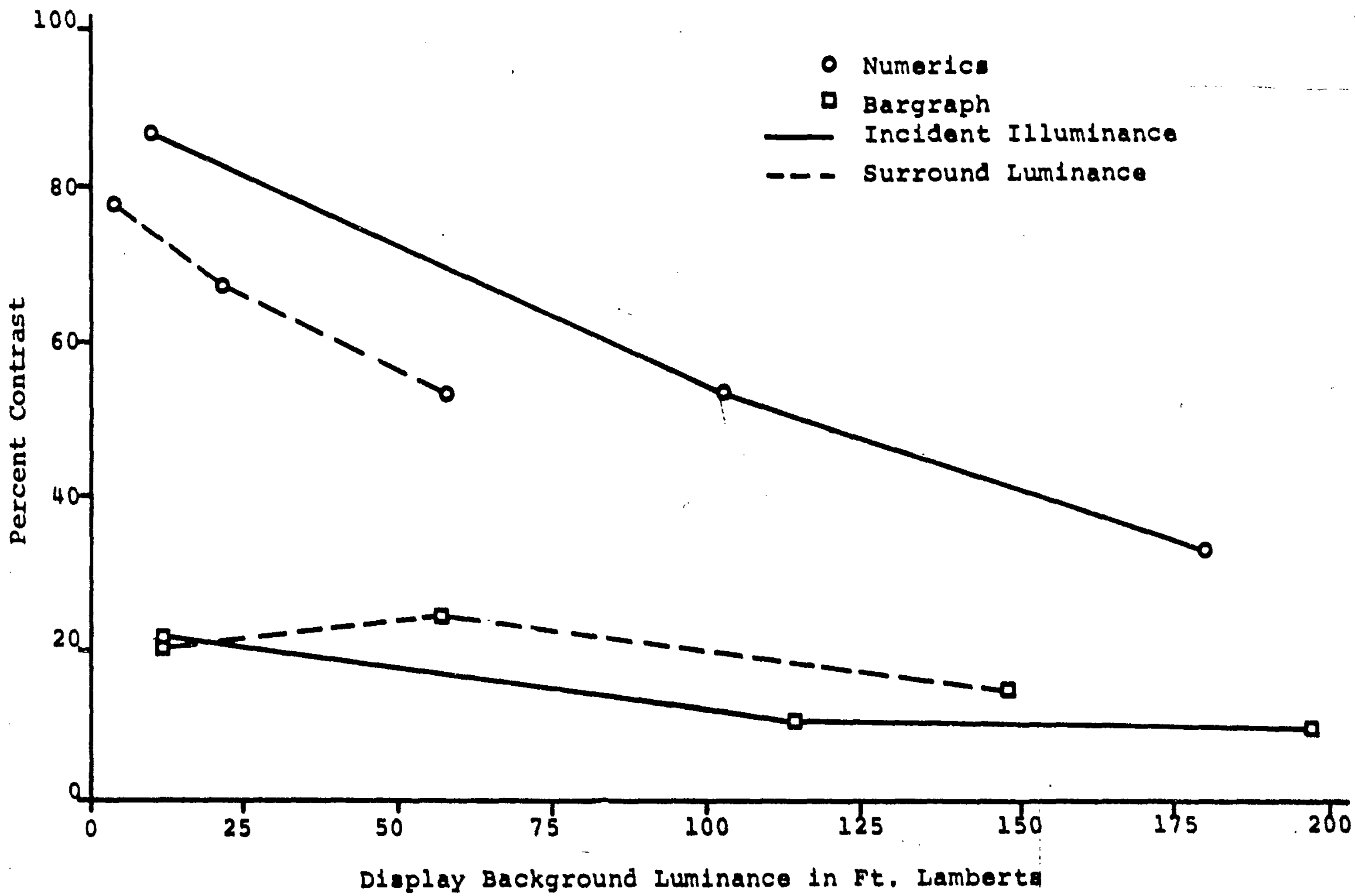


Figure 202. Percent Contrast Required for 99% Display Legibility. (Adapted from King et al., Ref. 208)

Table 102. Mean Legibility Percent Contrasts for Bargraph and Numerics as a Function of Whether a Helmet-Mounted Visor was Worn. (Adapted from King et al., Ref. 208)

		BARGRAPH		NUMERICS	
INCIDENT ILLUMINANCE		Without Visor	With Visor	Without Visor	With Visor
	5,000 Ft. L.	5.5	5.7	20.6	24.2
	10,000 Ft. L.	4.4	4.7	16.5	18.2
SURROUND LUMINANCE		Without Visor	With Visor	Without Visor	With Visor
	3,165 Ft. L.	8.1	7.3	31.9	39.8
	8,617 Ft. L.	5.6	7.1	24.5	31.3

are to reduce symbol and display background luminances and eye adaptation level, and since taking these factors into account did not eliminate the visor effect, then it is possible that surface reflections on the visor itself may have been the significant factor. This assumption is substantiated by the data of King et al. The effect of the visor was most pronounced for numeric readouts, which were comprised of stroke segments. It would seem that surface reflections would be a greater problem with segmented numerics due to possible interferences with the form perception task required to read the numerics. Reading the bargraph, on the other hand, required only the discrimination of the "on" area from the "off" area, a considerably less complex task. The validity of this hypothesis remains to be established.

Luminance data showing what King et al.'s subjects considered to constitute "comfortably bright" displays are summarized in Table 103. Corresponding emitted symbol luminance data are shown in Figure 203. Data in the table and figure are for the 50th percentile of the comfort-level judgement distributions. Use of the helmet-mounted sun visor had no impact upon the comfort-level judgements; consequently, these data are not shown.

The comfort-level symbol luminance data shown in Figure 203 are of particular interest. First, a comparison of Figure 203 with Figure 201 shows that median comfort-level luminances are consistently greater than corresponding minimum legibility luminances. In other words, given a choice, pilots will increase symbol luminances above those minimally required for legibility. Also of importance is the fact that no simple multiplier can be used to increase legibility luminances to comfort-level luminances. Bargraph comfort-level luminances ranged from 4.4 to 2.8 times corresponding legibility luminances, with the smaller factors being associated with higher display background luminances. Similarly, numeric readout comfort-level luminances vary from 2.5 to 1.1 times corresponding minimum legibility luminances. It also is apparent from this comparison that, even though the bargraph could be consistently read at lower emitted luminances than the numerics, pilots chose to increase the luminances of the bargraph by greater factors than the numeric. This observation is further apparent when one compares the two curves shown in Figure 203. Emitted luminances for the numerics ranged from 2.1 to 1.5 times the corresponding luminances for the bargraph, with the smaller factors again being associated with the higher display background luminances. These observations are of interest because the simple multiplicative relationships found between bargraph and numerics emitted luminances for legibility do not hold for comfort-level luminances. It is apparent, however, that relationships exist; they are not, however, simple relationships. It is again of interest to note, however, that data derived under the incident and surround illumination conditions fall on a smooth curve as a function only of display background luminance,

Table 103. Fiftieth Percentile Percent Contrasts and Emitted Luminances Required to Produce Comfortably Bright EL Displays. (After King et al., Ref. 208)

Incident (Over the Shoulder) Illumination Conditions

Illumination Level in Ft. Lamberts	Bargraph B	Bargraph %C	Bargraph E	Numerics B	Numerics %C	Numerics E
0	0	--	0.08	0	--	0.12
500	11.8	66	7.8	10.4	89	9.2
5,000	114.1	39	44.5	103.0	58	59.7
10,000	197.0	28	55.2	181.2	44	79.7

Surround (General Canopy) Illumination Conditions

Illumination Level in Ft. Lamberts	Bargraph B	Bargraph %C	Bargraph E	Numerics B	Numerics %C	Numerics E
0	0	--	0.06	0	--	0.11
500	11.8	35	4.1	4.0	159	6.4
3,200	57.1	52	29.7	21.1	171	36.1
8,600	148.8	34	50.6	58.2	105	61.1

B = Display Background Luminance in Ft. Lamberts

%C = Percent Contrast

E = Emitted Symbol Luminance in Ft. Lamberts

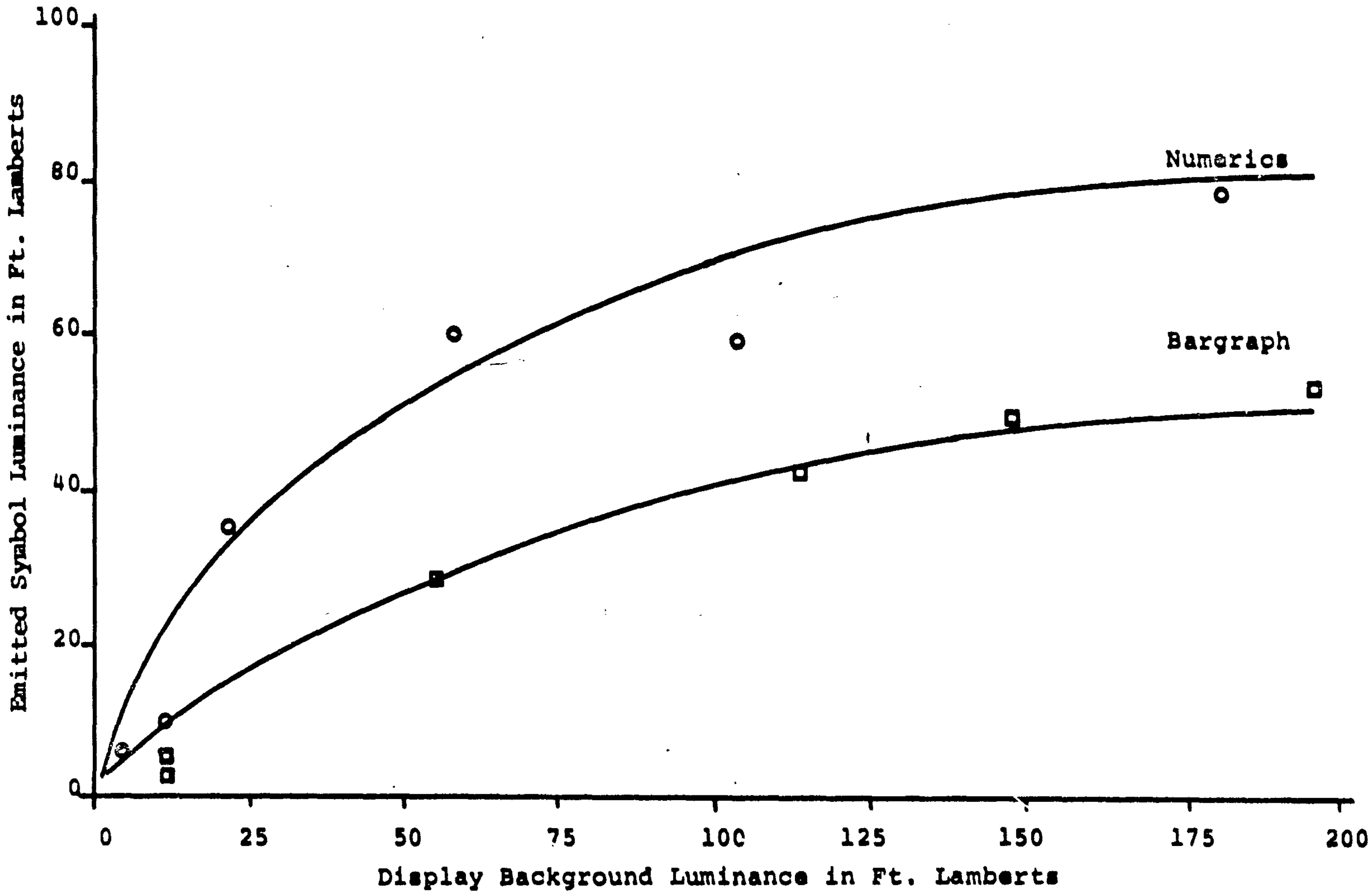


Figure 203. Emitted Symbol Luminance Required for EL Displays to be Judged Comfortably Bright 50% of the Time. (Adapted from Ref. 208)

again indicating that display background luminance is a considerably stronger variable than eye adaptation level in determining symbol luminance requirements.

Finally, King et al. report that the amount of time required to read each display decreased as display emitted luminance was increased to comfort-levels. This has significant impact upon minimum legibility contrast ratios as design criteria, since pilot reaction times to minimally contrasty symbology may not be that which is required in operational settings.

Projected Displays

In examining the early literature which might be applicable to predicting symbology luminance requirements for head-up displays, Kelley et al. (Ref. 195) concluded that the only possibly applicable data were those generated by Steinhardt (Ref. 322) in 1936. Steinhardt's data indicated that the ratio of added brightness to background brightness necessary to make a square of 31 minutes of visual angle just perceptible is approximately 4.0% at 10,000 Ft. Lamberts. Kelley et al. point out, however, that Steinhardt's data deal only with the absolute threshold for two surfaces of the same color, and were generated using a visual discrimination task which was judged by Kelley et al. to be easier than the visual discrimination task required with head-up displays.

Kelley et al. (Ref. 195) report a study in which it was intended to determine symbol luminances necessary for symbol legibility and discriminability of head-up displays (HUD) under conditions of high display background luminances. The HUD configurations consisted of 20 combinations of horizon line angle and angle of attack index location in relation to the horizon line. The display configurations were selected to provide an easy display discrimination (horizon angle) and a difficult discrimination (location of small angle of attack index). Symbol dimensions are shown in Table 104.

Table 104. HUD Display Symbol Dimension.
(from Kelley et al., Ref. 195)

Display Element	Size (inches)	Visual Angle* (degrees)
Horizon Line Length	3.0	6.75
Horizon Line Width	0.018	0.040
Angle of Attack Length	0.200	0.440
Angle of Attack Width	0.018	0.040

*Viewing Distance 26 Inches

A slide projector arrangement was used to present symbology on the HUD combining glass. A green filter (Corning C.S. 4064 unpolished) made the projector light output closely match the color of symbology which would be produced on a CRT using a P-31 phosphor. Data were collected using four different combining classes. Characteristics of the glasses are shown in Table 105. The trichroic filter blocked light passage between 500 and 550 millimicrons (green).

Table 105. Photometric Data on Combining Glasses.

Code	Combining Glass	Reflectance* 45°	Reflectance* 67°	Transmissions* 45°	Transmissions* 67°
	Calibration (Front Surface of Optical Mirror)	100	100	0	0
A	Plate (Uncoated 3/8 Inch)	29	24	85	79
T	Trichroic Coated 1/8 Inch	70	25	63	63
X	Partially Silvered Plate (1/4 Inch)	31	31	66	60
W	Window Glass (1/8 Inch) Anti-Reflectance Coated	7	21	90	84

* Reflectance measurement of Green Display Symbol Surface; Transmission of Xenon White Background

Ten participants in the study looked through the combining glass into the 10,000 Ft. Lambert luminous background. Symbol luminance was adjusted over 50 trials per participant to determine luminance required for subjects to correctly identify the display configuration 9 out of 10 times (i.e., a 90% threshold). Subsequently, subjectively comfortable display brightnesses were determined. Not all subjects received each combination of experimental conditions. Finally, some combination of conditions were experienced by only one or two participants. At most, only four different participants provided data for any one combination of conditions. His data are summarized below. Practically all data were collected under conditions in which participants did not wear sunglasses. Only one subject wore sunglasses under one condition, and the use of the glasses did not appear to have any marked influence upon the 90% threshold data. These factors not withstanding, Kelley et al. have published the only experimental

data directly dealing with HUD symbol visibility. The data are summarized in Tables 106 and 107.

The data shown in Table 106 for 90% thresholds of identification are quite limited, but do appear to show a general superiority for the trichroic coated combiner. They also show the influences of task difficulty. Identifying angle of attack marker position required increased ratios in relation to those required simply to identify horizon line angle. Of particular interest are the data in Table 107 which again show that, given an option, individuals prefer to have symbols more luminous that minimally required for legibility or interpretability. Also of interest is the observation that brightness contrast recommendations based upon Steinhardt's laboratory data (Ref. 322) would not have proved sufficient for display application.

RESEARCH RECOMMENDATIONS

Electronically-generated flight data displays are becoming quite common in advanced airborne systems, and consequently there is a pressing requirement for symbol contrast design information. A review of the available literature indicates, however, that there are practically no design-oriented contrast data available which may be used for a variety of flight display applications with any degree of certainty. The more comprehensive, parametric data which exist (e.g., Blackwell's data) were collected in a basic laboratory setting. Recent research (e.g., King et al) has shown that factors such as symbol type markedly influence legibility contrast requirements, and existing parametric data simply do not take this or many other factors of equal significance into account. Finally, there are very few data which address the problems of head-up display luminance requirements. Clearly, there is a pressing need for legibility contrast data which are design-oriented in nature. The number of design variables which must be considered in generating design-oriented, generalizable contrast ratio data is quite large, with some of the variables having only recently been identified as impacting upon contrast ratio requirements. Variables and ranges of variables requiring investigation are addressed below. It is known that many of the variables interact. Any research addressed toward producing design-oriented data simply must take the interactions into account. Single-thread, single-variable studies simply will not produce the needed data.

Display Background Luminance

There is no single legibility contrast ratio. Rather, contrast ratio requirements and therefore symbol luminance requirements vary as a function of display background luminance. Design-oriented contrast ratios for head-down display application should be established for display background luminances ranging from 0.1 Ft. Lamberts up to 1,000 Ft. Lamberts. For head-up

Table 106. Ninety Percent Threshold Data for Fine (Angle of Attack) and Coarse (Horizon Angle) Tasks. (Adapted from Kelley et al., Ref. 195)

Mean Luminances and percent contrasts necessary to result in participants correctly identifying angle of attack symbol position nine times out of ten.

Combiner* Code	Background Luminance of Combiner (Ft. L.)	Symbol Luminance (Ft. L.)	Percent Contrast
A-45*	8200	683	8.3
A-67	7200	582	8.1
T-45	6500	272	4.2
T-67	No Data		
W-45	No Data		
W-67	No Data		

Mean luminances and percent contrasts necessary to result in participants correctly identifying horizon angle nine times out of ten.

A-45	8200	420	5.1
A-67	7200	437	6.0
T-45	6500	201	3.1
T-67	No Data		
W-45	No Data		
W-67	10,000**	480	4.8

* Refers to Combiner Code shown in Table 105 and associated Mounting Angle in Degrees.

** Based upon a 12,500 Ft. Lambert luminance in front of the Combining Glass.

Table 107. Summary of Comfort Level Symbol Contrasts Ratio for Most and Least Sensitive Subjects, (Adapted from Kelley et al., Ref. 195)

Subject	Combining Glass	Contrast Rates in Percent
PHS	Clear	21.9
JK	Clear	42.6
PHS	Clear, sun glasses worn	20.0
JK	Clear, sun glasses worn	25.0
PHS	trichroic	13.8
JK	trichroic	18.5

display application, the range of background luminances is from 0.1 Ft. Lamberts up to 8,000 Ft. Lamberts. For head-up application, however, considerations of trichroic or other similar display filtering must be considered. It is recommended, therefore, that the establishment of contrast ratios for head-up application should involve magenta (minus-green) display background color, and green symbology in order to give proper consideration to color contrast.

Filter Types

Ultimately, filter technology and further development efforts must specify the types and characteristics of filters for electronic display application. It would appear, however, that the effects upon display background luminance and display legibility should be established for the following types of filters: thin film high-contrast; micromesh; wire-mesh; circular polarizing; and combinations of these. The effects should be established for direct incident illumination conditions up to 10,000 Ft. Candles. Additionally, the angle of the incident illumination source should be varied from 90 degrees to 180 degrees relative to the plane of the electronic display face in both vertical and horizontal axes.

Eye Adaptation Levels

Luminance levels to which the pilot's eyes may be adapted can cover a range of from 0.1 Ft. Lamberts up to approximately 8,000 Ft. Lamberts. Effects upon display legibility are not pronounced as long as the adapting luminance does not exceed eight to ten times the general display background luminance.

Adapting luminances, none-the-less, must be included in contrast ratio research, with the selection of adapting luminances being made in conjunction with display background luminance levels.

Sun Visors

The effects of helmet-mounted sun visors must be established for cockpit and sky luminance levels greater than approximately 1,000 Ft. Lamberts. The visors and glasses used should conform to Air Force specifications for color and transmitivity. There is evidence that the use of such devices does more than simply adjust the luminance level to which the eyes are adapted. Recent experimental evidence shows that the use of helmet-mounted visors interacts with symbol characteristics to influence minimum legibility contrast ratio requirements. Recent research, however, also has shown that the use of helmet-mounted sun visors results in no statistically significant change in contrast ratios or display reading times when symbology is bright enough to produce "comfortably contrasty" display presentations. Consequently, as display technology improves to the point where comfortably bright and contrasty symbology can be consistently obtained, there may be no requirement to take the use of sun visors into effect. Until such assurance is real, however, the effects of sun visors and sun glasses must be considered experimentally.

Emitter Characteristics

The reflectance characteristics of display emitters are integrally involved in the control of display background luminance. Depending upon design techniques used, it is known that display phosphors and other components may not only reflect incident luminance, they also may flouresce. For CRT type displays, there appears to be the potential for decreasing reflected luminance through the use of transparent phosphors and light trapping tube design. Although it is beyond the purvue of this study to provide detailed recommendations for research relating to emitter characteristics, it is apparent that such research and development holds considerable promise in providing design guidance for electronic flight displays.

Symbol Type

Electronically-generated display symbology comes in a variety of types and kinds. Because symbol type is known to influence contrast ratio requirements, it is necessary to establish requirements imposed by representative symbologies. The most simple symbology involves a bifurcation of the total display, such as is found in attitude indicators incorporating a lighter above-the-horizon area and a darker below-the-horizon area. Beyond this, symbols came in two fundamental classes: outlined symbols and solid symbols. Considering outlined symbols first, it is recommended that contrast ratio requirements be established for

alphanumerics, crosses, circles and boxes, as well as for simple line segments ranging in length from .10 to 8 inches. Within the class of solid symbols, it is recommended that contrast ratios be established for solid circles, solid squares, solid crosses, and solid rectangles (i.e., bargraphs). Additionally, it would appear highly desirable to verify outlined symbol contrast requirements by establishing contrast requirements for scales such as those associated with altitude and angle of attack.

Symbol Size

Symbol size interacts with display background luminance in determining legibility contrast ratio requirements. For basic outlined symbols, such as alphanumerics, crosses, etc., symbol heights ranging from 0.13 inches to 0.75 inches should be examined. Stroke widths for such symbols typically should be from 13 to 20 percent of the symbol height. Thus, stroke width dimensions ranging from 0.015 inches to 0.150 inches should be examined, with this stroke range also applying to simple line segments of varying lengths. For solid symbols, the same overall symbol heights generally apply, although bargraphs ranging in height up to six inches should be varied experimentally. For solid symbols, stroke width would have to be chosen in conjunction with the particular symbols selected for experimentation.

Symbol Color

Because human visual perception is influenced by color combinations as well as brightness differences, it follows that contrast ratios derived using a chromatic symbology may not be directly applicable to colored symbology. No design-oriented data exist which relate to contrast ratio requirements as a function of symbol-background color combinations. The following colors have been found, by various researchers, to be easily distinguishable on an absolute basis: Reddish blue, greenish blue, bluish green, green, green-yellow, reddish yellow, yellow-red, and red. Additionally, "white" symbology must be investigated. It would appear most practical to establish design contrast ratios for white symbology initially, because of the prominent use and anticipation for use of black-and-white CRT presentations of flight information. However, solid state displays frequently incorporate colored symbology. It is to be hoped, at least, that data could be generated which would allow the generalization of black-and-white symbology contrast requirements to colored symbology, based upon rules for extrapolating brightness contrast data to color contrast design problems. It is felt that the investigation of black-and-white symbology should take precedence over colored symbology. This recommendation, however, must be implemented with due consideration to future display system developments, particularly with regard to solid state displays and color CRT displays.

Solid State Display Resolution

Light emitting diodes, gas discharge tubes and electroluminescent displays are characterized by the fact that display formats are made up of arrays of emitters. The emitters may be arranged in an X-Y matrix, or in the case of alphanumerics the emitters may consist of line-shaped segments arranged in any of a number of patterns. In either arrangement, emitter size and shape may be varied, as may emitter placement, at least within the current limits of the state-of-the-art. Because each emitter is a separate element and because gaps or other types of spaces occur between the emitters, solid state display symbology typically is not made up of solid, continuous lines or solid areas. Solid state display technology is relatively new. Consequently, practically no human factors studies have addressed solid-state display design, although those which have have dealt primarily with legibility contrast ratio requirements. The data base is far from complete and does not cover the continuum of emitter sizes, shapes and placements which may be anticipated in the future. It is recommended, therefore, that solid-state display resolution characteristics be considered in the development of contrast ratio design data. Emitter size (area) and placement (spacing of emitters relative to other emitters) should receive primary consideration due to the fact that legibility is known to be influenced by the area of the eye's fovea which is stimulated by symbology. The selection of emitter sizes and emitter placement dimensions should be accomplished immediately prior to the initiation of such research, however, in order that the most current state-of-the-art technology and projections for technology may be incorporated.

Contrast Polarity

Available experimental data indicates that it makes little difference whether light symbols against a dark background are used, or visa versa. However, when a difference is found, it favors dark symbols against a light background. Since this finding favors the opposite of current practice in electronic display design, and since the data which are available do not systematically address flight display symbology or the flight illumination environment, it would appear highly desirable to at least identify the effects of symbol contrast polarity upon symbol discrimination and identification at the higher display background luminances which may be anticipated inflight.

Variable Interactions

Both recent and less recent research findings strongly indicate that a number of the variables discussed above interact to influence legibility contrast requirements. Based upon known interactions, it is only realistic to recommend that the following variables be studied in combination in order to produce meaningful

data; display background luminance, eye adaptation level, symbol size, symbol type, and sun visors and sun glasses. Considering the ranges of each variable which are of design interest, it is apparent that producing design-oriented contrast ratio data will be no small undertaking. Yet, the data are critically needed, not only to provide inputs to the display designer, but also to preclude the necessity for inefficient and frequently non-generalizable special purpose experiments.

Experimental Tasks

To provide the maximum generality, contrast ratio data which are generated should emphasize basic visual-perceptual tasks. It is not often that display design data can be meaningfully established out of system dynamics and operator task contexts. It is only a reasonable assumption, however, that regardless of the task-related use to which various types of symbology may be put, the symbology must be clearly visible. Consequently, experimental tasks to be employed in generating design-oriented contrast ratio data should emphasize visual-perceptual tasks. The following tasks are recommended, therefore, for use in experimental studies involving the generation of design-oriented contrast ratio data:

- Symbol discrimination, including the absolute identification of symbol shape and alphanumeric legibility. It would also be desirable to include simple line segments of appropriate dimensions.

- Scale reading, with emphasis on vertical and horizontal linear scales.

- Locating symbology on display faces which incorporate multiple symbols.

- Identifying and responding to attention-getting symbology, such as flashing indicators or special purpose annunciators.

- Secondary tasks also should be included in order to introduce time-sharing and attention-sharing requirements, thus precluding the possibility that contrast ratio data are biased toward overly simplified task contexts.

- Continuous control tasks also should be considered, if only to verify the generality of data generated using more basic visual tasks.

Performance Measurement

Academic-type performance criteria such as the 50% threshold of visibility have no value in display design. Rather, contrast ratios for display legibility require, at an absolute minimum,

that virtually 100% of the pilot population will at least be able to identify the presence and type of symbology presented. To assure either minimum or above minimum contrast ratios, the following display and human performance measurements must be made: display background luminance, symbol luminance, symbol color, display reading time or response time, and probability of correctly identifying or reading display symbology. Several combinations of these measures are discussed below.

At a minimum, contrast ratios required for virtually 100% correct symbol identification by virtually 100% of the user population are needed. Thus, at a minimum, mean contrast ratios plus three standard deviations are required for performance which demands several consecutive correct identifications of symbology. Beyond this, contrast ratios needed for correct performance with minimum reading or response time are needed. Indeed, this latter criterion makes the greatest amount of sense for cockpit display applications. Finally, given a brightness or contrast control knob, it is known that pilots will increase emitted luminance levels above those needed for minimum legibility. Since displays must be not only minimally usable, but also acceptable to the user, it follows that pilot preference must be taken into account, and "comfortably bright" display contrast ratio requirements established. Pilot preferences also should be recorded in conjunction with other variables such as symbol size in order that the most preferred out of equally acceptable values may be identified for other related display variables.

SECTION XI

ENVIRONMENTAL VARIABLES

INTRODUCTION

This section separately addresses the topics of ambient illumination, vibration and acceleration as environmental variables impacting upon electronic flight display system design and evaluation. Electronic flight display research has primarily been conducted under static, one g, moderately illuminated conditions. At the present time there is no known way to extrapolate these findings to the dynamic, variously lighted real-time environment. The following section presents the limited operationally acceptable data which are available. Research recommendations for each of the three topic areas are addressed at the conclusion of the section.

AMBIENT ILLUMINATION

Before proceeding, it is necessary to distinguish between measures of illuminance and luminance. The concept of illuminance (illumination intensity) involves the idea of interception of light flux by a surface. Illuminance, therefore, is measured in terms of the density of flux incident upon a surface. A commonly accepted measurement is lumens per square foot or the Ft. Candle. Luminance refers to the amount of luminous flux proceeding to the eye from a unit area of surface. Light reflected from or generated by a display may be specified in Ft. Lamberts, which is a measure of surface luminance.

A number of reports were reviewed in an attempt to identify the levels of illuminance and sky luminance which may be experienced by pilots during the course of performing operational missions. Results of the review are shown in Table 108, which presents ranges of illuminance values obtained by the several investigations. It can be noted from the table that different measurements produce different illuminance values for apparently similar situations. This is not surprising, particularly when one considers the difficulty in specifying a "standard" day. Additionally, it is argued by many that photometry is as much a black art as it is a science, principally because of the cautions which must be exercised in calibrating sensitive photometric measurement devices.

Of particular importance in Table 108 are the measurement estimates of direct sun illuminance, clear sky illuminance, and cloud luminance, because these measures provide data which may be used in estimating the maximum illuminance which may be incident upon the electronic display surface and the values to which the pilot's eyes may be adapted.

Additionally, Figure 204 is presented in order to provide data showing the relationship between solar altitudes and illuminance and luminance values which may be anticipated during flight. (Note, one millilambert is equal to .929 Ft. Lamberts.)

A review of the sun illuminance data shown in Table 108 indicates that an approximate average illuminance value for direct sunlight would be on the order of 11,000 Ft. Candles. Similarly, an approximate average luminance for a clear sky would be 2,000 Ft. Lamberts. Finally, a representative value for the luminance of "average" cloud cover would be approximately 7,000 Ft. Lamberts, although luminance of upper surfaces of clouds at midday could be expected to significantly exceed this value. Although these figures are admittedly approximate and based upon very loose definitions of representative atmospheric and meteorological conditions, they have been used in other report sections as representative computational values. The need for comprehensive and systematic measurement of representative atmospheric illuminance and luminance values is quite apparent.

Table 108. Summary of Selected Measurements of Natural Illumination in Earth's Atmosphere.

Illuminance of Sun in Earth Atmosphere		
Source	Value	Comments
Ketchel & Jenney (Ref. 206)	10,000 Ft. C.	"Accepted Norm."
Luxenberg & Bonnes (Ref. 225)	9,000 Ft. C.	
Duntley et al. (Ref. 110)	10,000 Ft. C.	Measurement made at sea level with sun at zenith. Time of year not specified.
Luxenberg (Ref. 224)	9,000 Ft. L.	White paper in direct sunlight.
Ketchel (Ref. 203)	9,000 -- 12,000 Ft. L.	(Range of values cited by Ketchel from review of such data.)
	14,300 Ft. L.	Maximum luminance reflected from a white surface at noon.

Table 108 -- Continued

Source	Value	Comments
Illumination of Sun in Earth Atmosphere (Continued)		
Christensen (Ref. 65)	14,300 Ft. C.	Measured in Plexiglass nose section of a B-17G aircraft at 50,000 feet.
Webb (Ref. 344)	14,700 Ft. C.	Sun at zenith.
Average Sky on Clear Day		
Christensen (Ref. 65)	3,000 Ft. L.	Brightness extreme for horizon.
	1,250 Ft. L.	Brightness 30° above horizon.
	600 Ft. L.	Brightness 60° above horizon.
Luxenberg (Ref. 224)	2,000 Ft. L.	Clear sky.
Webb Associates (Ref. 343)	1,860 Ft. L.	Average sky on clear day.
Ketchel (Ref. 203)	1,430 to 7,150 Ft. L.	Measured range of clear sky luminances, 1,000 to 15,000 feet of altitude, 10:00 - 12:00 hrs., Feb., Palo Alto, Calif.
Ketchel (Ref. 203)	2,900 Ft. L.	Representative luminance of clear sky, from measurements cited above.
Cloud Brightnesses		
Webb Associates (Ref. 343)	82,000 Ft. L.	Upper surface of clouds at noon.
Webb (Ref. 344)	8,200 Ft. L.	Average cloud cover at noon.
Christensen (Ref. 65)	6,200 Ft. L.	Scattered altocumulus clouds at 15,000 feet, measured in early afternoon during Oct. in Ohio.
Webb (Ref. 344)	1,100 Ft. L.	Average storm cloud cover at noon.

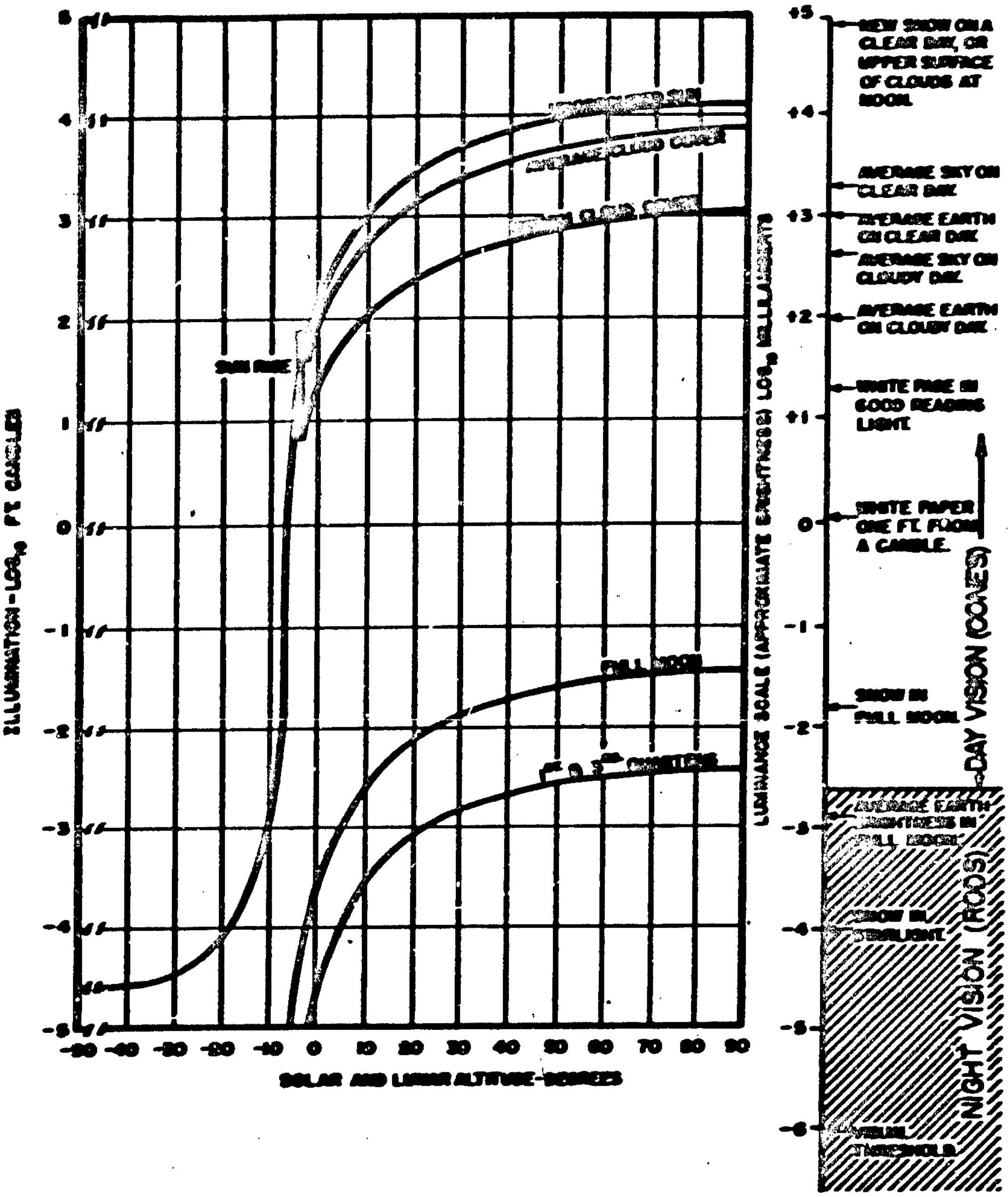


Figure 204. Range of Natural Illumination on Earth from the Sun and Moon. (Adapted from Ref. 343)

VIBRATION

Introduction

Exposure to low frequency, high amplitude vibrations characteristic of high performance aerodynamic, space and surface vehicles becomes an extremely important problem in terms of a crewmember's ability to perform successfully the tasks essential to the completion of the vehicle's mission (Ref. 78). Low frequency vibrations (generally below 70 Hertz) can be sinusoidal, complex, but systematic (consisting of two or more sine waves in combination), or they may be random (Ref. 230). Most of the vibration research conducted to-date has been of the sinusoidal type and can therefore readily be classified in terms of frequency and intensity. For a fixed frequency the following are successive derivatives of amplitude with respect to time:

Intensity Measurement	Formula
Displacement Amplitude (Xm)	Displacement from static position in inches
Maximum Velocity (Vm)	$2\pi f X_m$ in. per sec.
Maximum Acceleration (Am)	$4\pi^2 f^2 X_m$ in. per sec.^{2}
Maximum Jerk Amplitude (Jm)	$8\pi^3 f^3 X_m$ in. per sec.^{3}

Maximum acceleration is frequently used as a measure of vibration intensity or magnitude and is typically expressed in terms of gravitational units (g). The frequency is expressed as the number of cycles per second (Hertz) that the maximum acceleration occurs.

It would be extremely useful to have the vibration environment adequately defined for both fixed and rotary wing aircraft during functional mission segments. A review of the literature has produced some detailed vibration information for helicopters.

In a report by Ketchel, Danaher and Morrissey (Ref. 205), the vibration characteristics of contemporary military helicopters are described. Included in this report is a breakdown of MIL-H-8501A which specifies the military-imposed limitations on helicopter vibration. MIL-H-8501A contains the following:

> "For steady state speeds within the helicopter design flight envelope and in slow and rapid transition from one speed to another and during transitions from one steady acceleration to another, vibration acceleration at all controls shall not exceed 0.4 g for frequencies up to 32 cps and a double amplitude of 0.008 inch for frequencies above 32 cps."

This portion of the MIL-H-8501A specification covers the worst-case vibration conditions permitted in military helicopters, and provides baseline values which may serve as representative figures to compare with both operational and research levels of vibration established for helicopters.

Schuett (Ref. 292) reports that the helicopter vibration frequency spectrum ranges from about 3 to 110 Hertz. Ketchel et al. (Ref. 205) report that adverse effects occur in visual performance when vibration falls within the dominant main rotor frequency range of 10 to 30 Hertz. These authors also report that the degradation in performance tends to be more pronounced when additional complexities such as task difficulty, g-level, ambient lighting, insufficient contrast and workload are added.

Operational helicopter vibration data have been reported by Ketchel et al. (Ref. 205) from data derived by Seris and Auffret (Ref. 298) in a report on vibration for the Super Frelon 6-bladed, turbine-powered helicopter. Peak accelerations ranging from 0.3 to 0.5 g are reported for all three axes at the main rotor dominant frequency of 20.2 Hertz. Accelerations incurred above 15 Hertz are reportedly well dampened by the seat and the pilot's body, which led these authors to advise that the low frequencies from 3 to 7 Hertz result in maximum discomfort and are most difficult to dampen.

A review of the literature has not revealed any technically acceptable or operationally useful documents defining vibration for representative fixed wing jet aircraft. Getline (Ref. 136) published environmental vibration figures for the F-106A during various flight profiles, but both hard-copy and microfiche copy of this report are unreadable.

The objective of this section will be to present design-oriented research data dealing with the effects of various conditions of vibration on the legibility of primarily visual perceptual tasks such as reading or dial reading. The basic psychophysical data relating visual acuity to vibration will be mentioned only briefly, as there is no known way to quantitatively extrapolate these results into display design-oriented legibility data. Also, the motor performance-vibration literature has been omitted since it is not of direct relevance to a primarily visual readout task.

Visual Acuity

A flight display is a composite of elements whose individual legibilities may be affected differentially by vibration. Numbers, letters, symbols, lines, etc. are examples of these elements, and ideally the degradation in legibility for each of these should be specified for a range of vibration conditions appropriate to the aircraft flight conditions being considered.

In actuality, however, vibration research relating to visual perceptual tasks has been conducted primarily on basic visual parameters such as visual acuity. The following section briefly relates some vibration versus visual acuity findings.

In the absence of vibration and under ideal illumination and contrast conditions, the observer can resolve targets subtending visual angles of one minute of arc or less. The introduction of vibration will degrade this performance; the extent of the degradation is dependent upon the nature and intensity of the vibration. The degradation will take the form of dioptic as well as cerebral-intellectual disturbances. The transmission of vibration to the eyeball of the observer will tend to produce a shift of the image on the retina induced by ocular movement and temporary ocular deformation. The cerebral-intellectual impairment may result from the withdrawal of the observer's attention from his task due to the physiological and psychological stress introduced by the vibration.

Whole body vibration gives rise to complex oscillations of the head, producing labyrinthine stimulation which, in turn, gives rise to involuntary eye movement in spite of attempts to fixate. This displacement of the line of sight is not due completely to angular acceleration, but occurs also in the presence of linear acceleration acting upon the labyrinth (Ref. 393). Mercier (Ref. 236) suggests that head movement relative to the aircraft during acceleration (i.e., movement of head necessary to fixate on moving target) gives rise to blurred retinal images and consequently impaired visual acuity. At frequencies between 1.0 and 2.5 cycles per second, visual performance in display reading is gradually reduced as the amplitude of the following eye movements rapidly fall off with increasing frequencies (Ref. 107). At 3.0 to 4.0 Hertz, the head and shoulders resonate, resulting in a more marked reduction of visual acuity.

Lange and Coermann (Ref. 395) conducted a study to examine the effects of vertical sinusoidal vibration on the visual acuity of twelve subjects seated in an aircraft-type seat on a vibrating table. The frequencies investigated ranged from 1.0 to 20 cycles per second (Hertz). Illumination conditions were not specified (reported to be 'optimal'). A projection system displayed the targets on a screen 35 feet in front of the observer. The targets were 0.188 inch wide with a minimum visible separation between the targets of 0.125 inch.

The results of the study indicate that at 1, 2, and 4 Hertz, the mean decrement during vibration was found to be negative, indicating some improvement of visual acuity at those frequencies (Figure 205 and Table 109). The first substantial peak of decrement of visual acuity occurred at 5 Hertz, where all but two of the subjects showed loss of acuity (with a very small standard deviation in their scores). Between 8 and 10 Hertz there was an

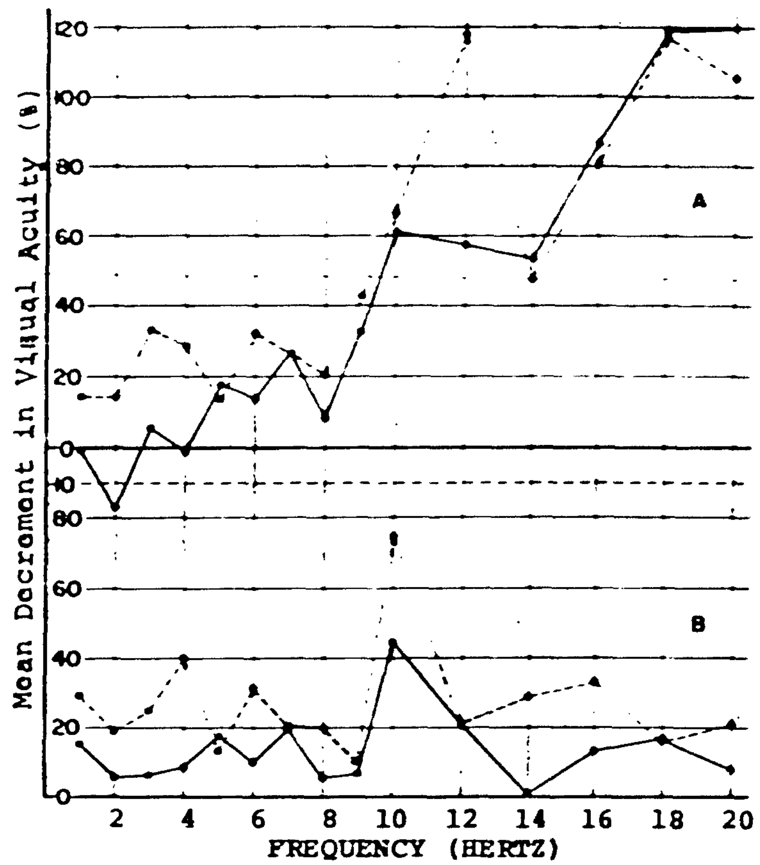


Figure 205. Mean Decrements of Visual Acuity (Solid Curve) and Mean Standard Deviation (Dotted Curve), (a) During Vibration, (b) After Vibration. (After Lange and Coermann, Ref. 395)

increase in decrement and deviation. A review of Table 109 indicates that maximum decrements in acuity occurred at 5, 7 and 10 Hertz, with the greatest loss being registered at 7 Hertz. Impairment above 12 Hertz was almost constant, with the exception of the slight peak at 18 Hertz. Residual effects of the vibration persisted for approximately one minute after the stress was removed.

Lange and Coermann conclude that above certain frequencies (5 Hertz), the visual decrement is directly proportional to the eyeball displacement (i.e., head movement) if it is not additionally reduced by other stress actions. They suggest that the critical flicker frequency of the eye is between 8 and 16 Hertz, that movement of the images at frequencies higher than this

Table 109. Summary of Percentage Degradation of Visual Acuity During (a) and One Minute After Cessation (b) of Vibration. (After Lange and Coermann, Ref. 395)

Subject at	1 c/s	2 c/s	3 c/s	4 c/s	5 c/s	6 c/s	7 c/s	8 c/s	9 c/s	10 c/s	12 c/s	14 c/s	16 c/s	18 c/s	20 c/s
A R	10	20	20	+26.7	+33	+86.7	50	+5.6	0	+92.0	20.9		+60	-100	+97
J P	0	9.1	12.5	0	+16	+40.0	+14	-9.1	16.7	+7.0	15.0	+41.7	5.8	+12	+41
C J	20	16.7	47	+18.9	+25.0	+44.4	+25.0	0	47.0	+31.0	40.0	50.0	12.0	+82.9	+82.0
R R	+3.0	10.5	3.0	8.0	9.0	5.0	+12.0	8.0	-31.0	+50.0	+17.0	+16.0	+44.0	+24.0	15.0
J R	-11.0	20.0	+19.0	13.0	+21.0	19.0	+16.0		+5.0	+18.0	+11.0		+27.0	-14.0	-79.0
J W	-4.1	20.0	+8.1	20.0	+11.0	7.3	+12.0	+15.0	+17.0	+22.0	+42.0	+30.3	+27.0	+61.0	27.0
W J	10.5	+7.4	21.0	5.3	-2.5	+5.3	+18.0	7.4	+21.0	+18.0	16.0	+26.0	+16.0	+102.0	+210.0
E W	3.0	18.0	40.0	29.0	+13.0	-29.0	0	18.0	+17.0	+100.0	-25.0	15.0	+201.0	+400.0	+400.0
P G	2.8	19.2	2.8	+10.8	+16.0	+23.1	20.0	+40.8	+19.0	+250.0	+18.0		+141.0	+290.0	200.0
V S	16.7	22.0	67.0	26.0	+28.0	4.4	+54.0	+20.0	+81.0	+65.0	+244.0	+104.0	+205.0	+98.0	-79.0
F D	25.0	45.0	50.0	50.0	0	5.0	10.0	25.0	+100.0	22.0	+200.0	+75.0	+150.0	-250.0	-100
D H	+26.0	10.0	-69.0	-42.0	13.0	+11.0	-75.0	+42.0	+108.0	+81.0	150.0	+152.0	+200.0	+67.0	-42.0
Mean	0.7	17.0	-5.6	1.07	+17.4	+13.55	27.2	+8.1	+32.5	+61.1	+57.4	-53.3	186.5	-118.6	120.3
Median	1.4	18.0	2.9	6.6	+18.5	+0.45	+11.0	+7.4	+19.0	+44.0	-19.0	-41.7	152.0	-90.4	80.5
Std Dev	14.14	14.0	11.2	28.1	11.45	31.9	26.6	20.2	42.6	66.8	117.7	47.5	80.8	116.7	105.0
Mean per g	1.75	16.6	1.37	0.81	+25.8	-17.8	42.0	-7.95	+21.4	+19.7	-26.5	26.1	+28.1	11.8	25.7
g Vector	0.4	1.02	1.66	1.32	0.675	0.76	0.65	1.02	1.52	1.54	2.16	2.04	1.05	1.71	4.68

a. Percentage Decrement of Visual Acuity During Vibration.

Subject after	1 c/s	2.5 c/s	3 c/s	4 c/s	5 c/s	6 c/s	7 c/s	8 c/s	9 c/s	10 c/s	12 c/s	14 c/s	16 c/s	18 c/s	20 c/s
A R	40.0	26.7	-20	+40.0	+33.0	+50.0	-17	33.3	20	33.0	0		24	-17	-25
J P	4.2	-25.0	0	+12.5	16.0	+17.5	9.0	21.0	8.3	16.0	8.3	17.5	10.0	14	9.0
C J	8.0	22.2	46.0	+33.3	+17.5	+58.9	11.0	+16.7	40.5	17.5	17.0	22.2	40.5	6.2	17.5
R R	14.0	16.0	11.0	2.6	+6.0	0	+11.0	2.6	+11.0	0	-9.0	5.0	3.0	9.0	6.0
J R	-40.0	2.5	+27.0	+8.0	+25.0	1.5	+16.0	2.5	+40.0	+18.0	-20.0	5.0	5.0	29.0	0
J W	+8.3	2.1	0	6.0	+24.0	24.0	0	6.0	0	1.2	+6.7	2.0	-6.7	+11.0	+19.0
W J	10.5	5.3	26.0	16.0	0	10.5	0	5.3	5.3	25.0	26.0	10.5	21.0	12.5	0
E W	0	6.0	50.0	24.0	0	44.0	+67.0	18.0	+3.0	+150.0	0	29.0	25.0	0	0
P G	+32.0	+7.7	0	+34.6	20.0	-23.1	0	+18.5	2.8	+250.0	9.7		25.0	20.0	20.0
V S	+69.0	22.0	+69.0	29.0	+17.0	22.0	+4.7	11.0	+19.0	+9.4	+15.5	15.0	-44.5	+17.0	-2.8
F D	+50.0	25.0	+25.0	61.0	0	0	+10.0	25.0	+10.0	+10.0	0	25.0	-10.0	+50.0	25.0
D H	+33.0	+33.0	+46.0	+100.0	+33.0	+53.0	+50.0	+25.0	+8.0	42.0	+15.0	58.0	77.0	+17.0	-50.0
Mean	-15.33	+5.04	+6.33	+8.65	+17.6	+10.0	+19.6	+5.6	+6.34	+44.7	21	0.6	13.0	16.6	-7.2
Median	+11.1	+2.8	+15.5	+1.7	-18.5	0	+10.5	0.05	+5.5	+17.0	0	5.0	-9.5	+17.0	-1.4
Std Dev	29.3	18.85	24.7	40.1	11.0	11.2	20.8	19.8	9.85	74.5	20.75	28.5	13.0	15.5	21.0
Mean per g	+17.7	+5.5	+3.82	+6.55	26.1	13.15	+10.2	5.5	+4.16	+29.0	0.974	0.294	4.26	-4.45	1.64

b. Decrement of Visual Acuity One Minute After Cessation of Vibration.

cannot be analyzed by the brain, and that the images become blurred.

In two studies by Loeb (Ref. 218), reported in Dennis (Ref. 105), frequencies of 15, 20, 25 and 35 Hertz were examined. Loeb suggests that 'damping' between the vibrating table and the head (at 20 Hertz) is at least 60%, and this corresponds fairly closely with the results found by Dennis (Ref. 105) which indicate a damping effect of about 67% at 19 Hertz. A summary of Loeb's findings concerning acuity degradation is presented in Table 110. Unfortunately, these data cannot be combined due to varying viewing conditions and experimental design. A definite trend, however, can be discerned in the tables. Increasing the frequency of vibration above 15 Hertz, for example, appears to reduce the percentage of acuity degradation.

Table 110. Results from Loeb Showing % of Acuity Decrement per Estimated Head Movement. (Data from Loeb, Ref. 218, Reported in Dennis, Ref. 105)

Vibration Condition		Estimated Head Amplitude (In.)	% Acuity Decrement	% Acuity Decrement per 1/1000" Head Movement
Frequency (CPS)	Amplitude (In.)			
15	0.012	0.005	28	2.8
15	0.02	0.008	33	2.1
20	0.006	0.002	10	2.5
20	0.017	0.005	30	3.0
25	0.006	0.0012	15	6.3
25	0.010	0.0020	16	4.0
35	0.0055	0.0006	14	11.7
35	0.0095	0.0010	19	9.5

Dennis (Ref. 105) conducted an experiment to examine the degradation effect on visual performance resulting from the introduction of various intensities and amplitudes of vibration. Twelve subjects viewed printed numbers at a distance of 10' 11" (numbers subtended 5 minutes of arc) against a background reflective luminance of 0.1 Ft. Lamberts. Under these conditions, the subjects made about 15% error in the non-vibrating condition. The vibration amplitudes and frequencies are summarized in Table 111.

The results from this study indicate that visual performance was significantly affected at all frequencies when the motion of the vibrating table approximated ±0.5g (heavy vibration) and at all but one condition (19 Hertz) when the apparent movement approximated ±0.25g (light vibration). Heavy vibration had a

Table 111. Amplitude and Frequencies of Vibration in Study by Dennis, (Ref. 105).

Amplitude (Inches)	Frequency to Nearest Cycle per Second 'Light' Vibration (±½g)		'Heavy' Vibration (±½g)	
0.1	5	(AL)	7	(AH)
0.05	7	(BL)	10	(BH)
0.025	10	(CL)	14	(CH)
0.012	14	(DL)	20 (19)	(DH)
0.006	20 (19)	(EL)	28 (27)	(EH)
0.003	28 (27)	(FL)	40 (37)	(FH)

where:
A = 0.1 in. amplitude
B = 0.05 in. amplitude
C = 0.025 in. amplitude
D = 0.012 in. amplitude
E = 0.006 in. amplitude
F = 0.003 in. amplitude
L = 'Light' Vibration
H = 'Heavy' Vibration

significantly different effect on performance than did light vibration. Generally, light vibration increased error rates over non-vibration condition by about 22%, while heavy vibration further increased this figure to 55% (Table 112 and Figure 206). These results are in substantial agreement with the findings in a similar study by Coermann (Ref. 77).

Summary

The presence of vibration in a visual display situation adversely affects visual acuity. The extent of the visual degradation is a function of:

- frequency of the vibration
- amplitude of the vibration

With frequencies of vibration up to approximately 4 Hertz, slight visual degradation is observed. The first significant degradation occurs at 5 Hertz (from 10% to 20% degradation, depending upon amplitude). At frequencies between 8 and 10 Hertz, the result is 20%-plus loss of acuity. From 9 to 16 Hertz, approximately 50%-plus degradation and symbol blurring occurs. Vibration amplitudes of ±0.5g will increase visual degradation at all frequencies.

Table 112. Performance Degradation as a Function of Vibration Amplitude and Frequency. (From Dennis, Ref. 105)

Vibration Condition	Hertz	Table Amplitude (in.)	Head Amplitude (in.)	% Error Increase	% Error Increase per 1/1,000" Head Amplitude
*AL	5	0.1	0.1	44	0.44
AH	7	0.1	0.049	77	1.60
BL	7	0.05	0.032	13	
BH	10	0.05	0.022	46	2.1
CL	10	0.025	0.012	18	1.5
CH	14	0.025	0.011	92	8.4
DL	14	0.012	0.005	34	6.8
DH	19	0.012	0.004	42	10.5
EL	19	0.006	0.002	-1	-
EH	27	0.006	0.0012	28	23.3
FL	27	0.003	0.0007	23	32.9
FH	37	0.003	0.0003	49	163.3

*A = 0.1 in. Amplitude
B = 0.5 in. Amplitude
C = 0.025 in. Amplitude
D = 0.012 in. Amplitude
E = 0.006 in. Amplitude
F = 0.003 in. Amplitude

L = "Light" Vibration
H = "Heavy" Vibration

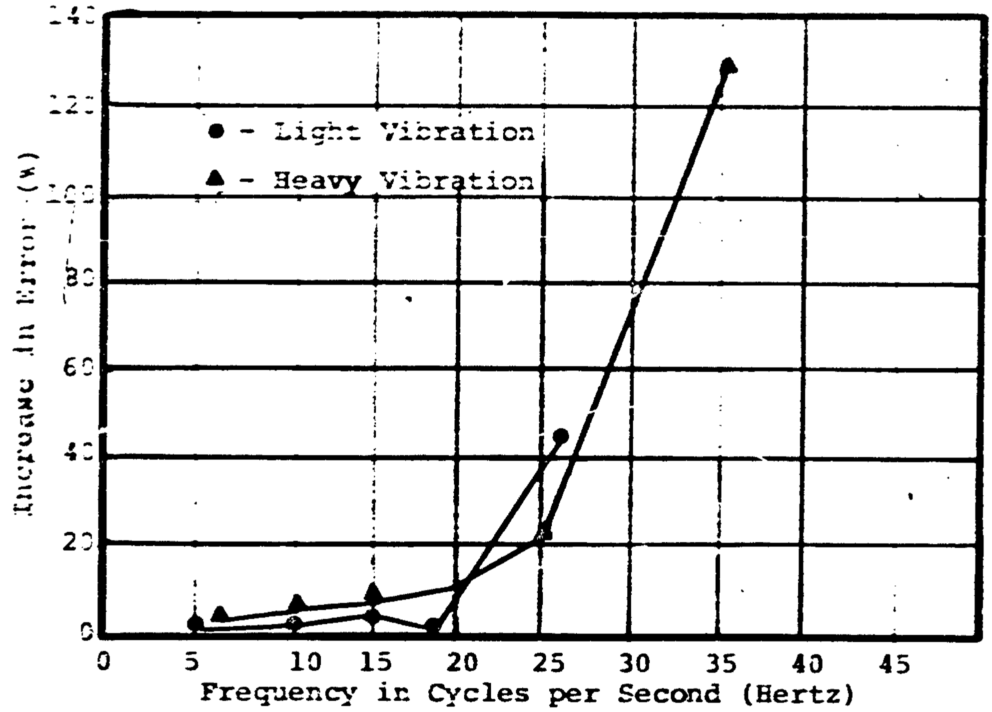


Figure 206. Percentage Increase in Error (per 1/1,000 Inch Amplitude) as a Function of Frequency of Vibration. (After Dennis, Ref. 105)

Dial Reading

Taub (Ref. 327) performed a series of studies to determine the vibration effects upon accuracy of reading performance for dial displays which represent a range of difficulty for the dial reading task. Dials consisted of photographs of circular dials with white markers and numerals against a black background. In the first study of this series, two types of dials were investigated (Figure 207), (1) the "easy" reading dial with a scale range of 0 to 50 with minor markers at units of 5 and major markers with numbers at units of 10; and (2) the "difficult" reading dial with a scale range of 0 to 400 with minor markers at units of 5, intermediate markers at units of 10, and major markers with numbers at units of 40. At a viewing distance of 28 inches, the "easy" dial major markers subtended a visual angle of 108.04 minutes of arc and the minor markers 21.61 minutes of arc. The difficult dial subtended 13.49 minutes of arc for the major markers and 2.71 minutes for the minor markers. The dials were mounted on a shaketable with the seat, which resulted in both the target and observer being vibrated simultaneously. Nine subjects viewed the dials at a dial luminance of 26.80 millilamberts and a background luminance of 2.68 millilamberts. Vibration consisted of a whole-body x axis,

(AGARD standard terminology) at frequencies of 6, 11 and 15 cycles per second and magnitudes of $\pm 1.2g_x$ and $\pm 2.0g_x$.

The results for the 400 range dial were presented two ways. First, each of the error scores was converted into a percentage and presented as total errors; second, gross errors were established as readings rounded-off to the nearest marker which were in error by three or more units. These, in turn, were converted into percentages. Results for the 50 range dial were presented as total errors only. Figure 208 presents the mean dial reading errors for the vibration conditions tested and the mean error scores for the static (no vibration) control condition. Both the 50 and 400 range dials had previously been tested in a static condition by Kappauf and Smith (Ref. 193), who had established a 5.4 percent and 28 percent static reading error rate for the respective dials. These error rates are roughly comparable to the static control conditions where 33.6 percent total errors was established for the 400 range dial and 3.98 percent total errors for the 50 range dial. A comparison of the vibration data presented in Figure 208 with the Kappauf amd Smith data and control condition static error rates indicates that the "difficult" 400 range dial was more severely affected by vibration than was the "easy" 50 range dial.

Tests of significance were not performed on the "easy" 50 range dial due to a J-shaped and markedly heterogeneous distribution of scores which violate the assumptions of the analysis of variance (non-parametric analysis was considered inappropriate). It is observed, however, from Figure 208, for the 50 range dial that vibration had essentially no effect at $\pm 1.2g_x$ and very little effect at $\pm 2.0g$ in comparison with the control condition. An analysis of variance for the "difficult" 400 range dial for both total and gross errors produced significant differences for acceleration amplitude, but not for frequency. A statistical comparison of the 400 range vibration scores with the control (static) condition indicated that (1) the total error criterion led to significantly (.01 level) more errors for all vibration conditions, and (2) the gross error criterion for $\pm 1.2g_x$ at 6cps and for all of the $2.0g_x$ vibration condition led to significantly (.01 level) more errors than the control condition. The results of this study, therefore, suggest that performance with the "easy" 50 range dial was not affected by the vibration condition tested, while reading errors with the "difficult" 400 range dial varied directly with the amplitude of acceleration. Frequency did not produce significant differences in the data.

After interpreting and reporting the results of this study, Taub concluded that a high subject variability may have obscured some of the true effects in the experiment. He therefore decided to partially replicate the first study using sixteen subjects (thirteen from previous study). Conditions were very similar to those previously reported, except that only the

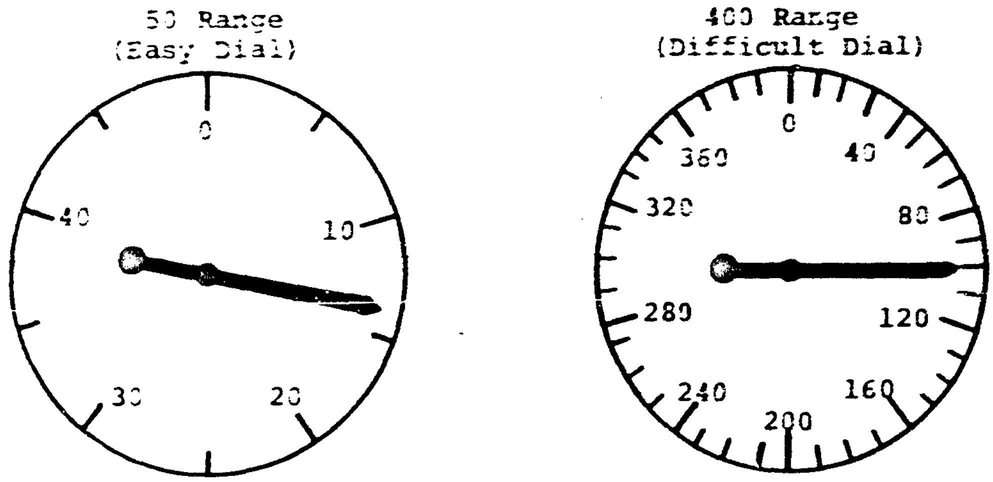


Figure 207. Approximations of Dials Used by Taub.

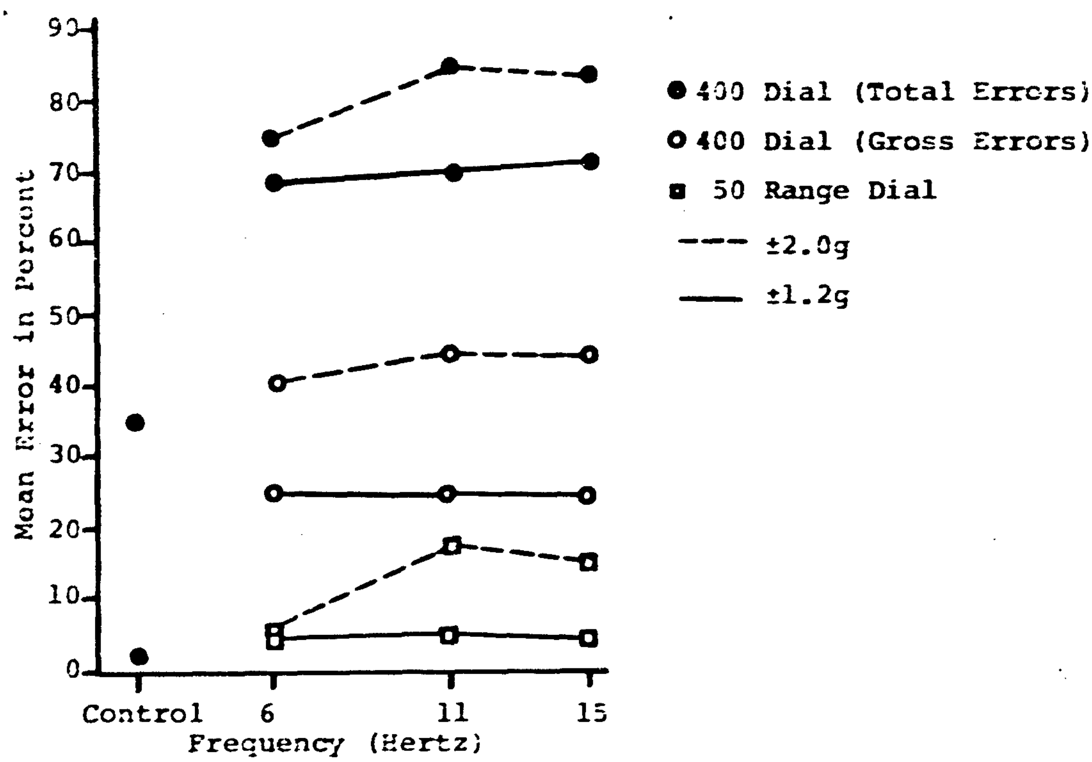


Figure 208. Errors as a Function of Frequency, Acceleration Level and Dial Type for Vibration in the X-Axis. (Adapted from Ref. 327)

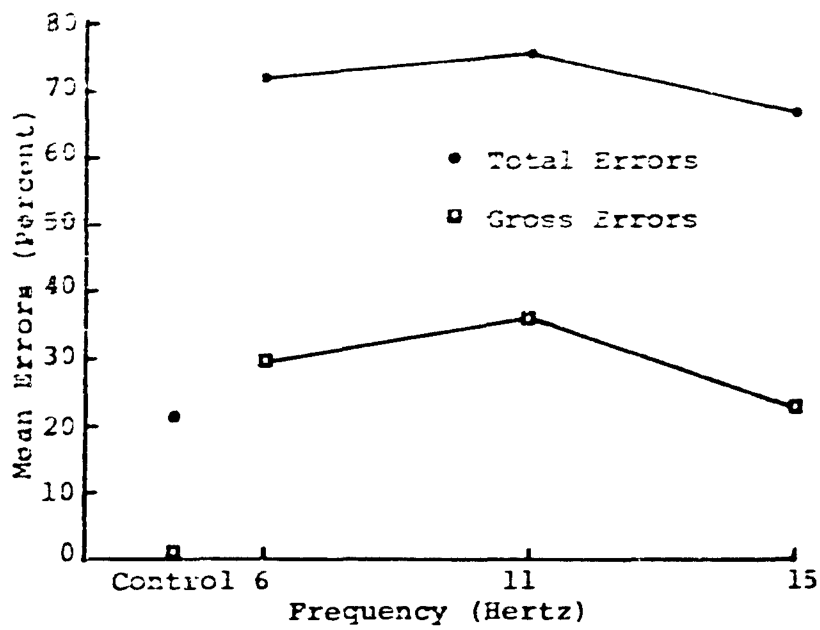


Figure 209. Errors as a Function of Frequency for Vibration in the X-Axis. (Adapted from Ref. 327)

"difficult" 400 range dial was tested at a single vibration amplitude of $\pm 1.2g_x$. There were some additional procedural differences involving run times and rest periods, but they will not be elaborated here. Under the changed conditions, an analysis of variance of the results indicated that frequency was a significant source of variance for both total and gross error scores (Figure 209). Performance was poorest at the 11 Hertz frequency. Further statistical analysis indicated that all vibration conditions for both total and gross criterion produced significant (.05 level) increases in error scores in comparison to the control mean.

Taub concluded from the combined results of these two similar experiments that, in general, performance was affected by the difficulty of the task, level of acceleration and frequency of vibration (with performance being poorest at 11 Hertz).

Clarke et al. (Ref. 72) also studied dial reading performance for conditions of vibration and acceleration presented simultaneously to subjects rotated on the NASA Ames Centrifuge. This effort was concerned primarily with the combined effect of the vibration and acceleration parameters generated by the booster motors of aerospace vehicles. Utilizing the Ames five degree of motion centrifuge, a sustained $3.8g_x$ acceleration was

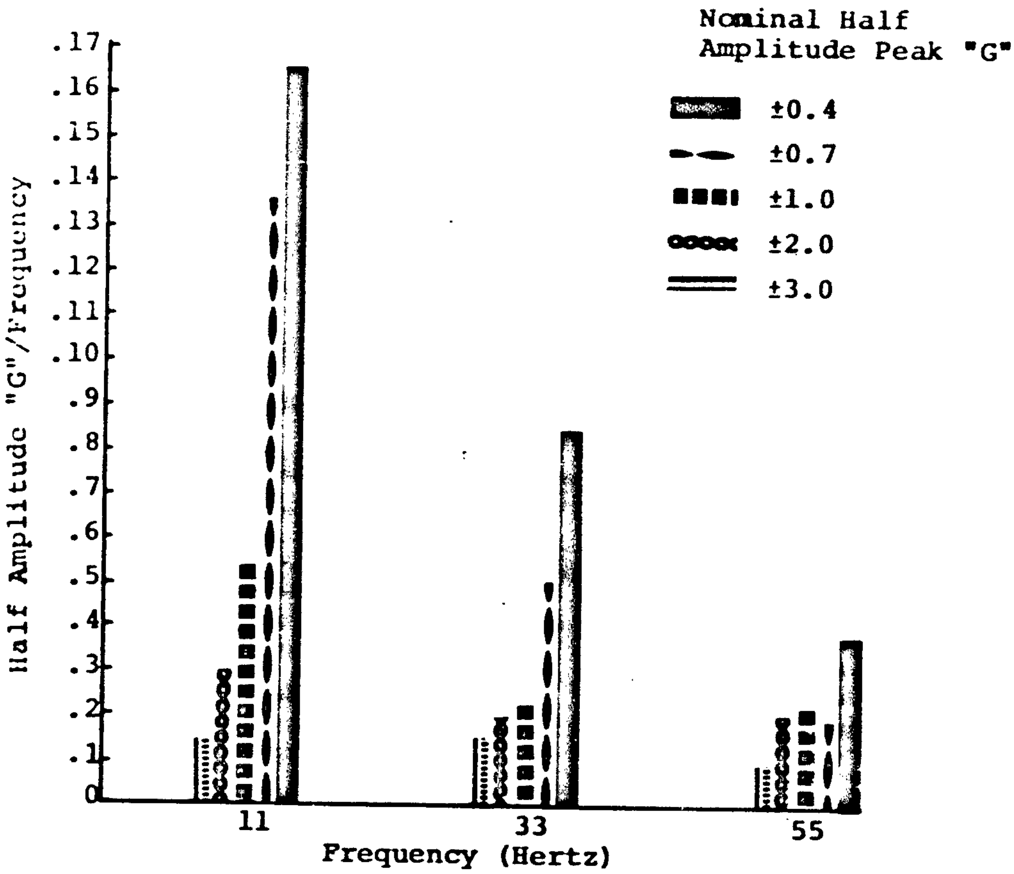


Figure 210. Power Density Spectrum of Vibration Input Acceleration.
(This figure shows that an acceleration of $\pm 3.0G_x$ contained third and fifth harmonies which comprised approximately 45% of the input signal. In other words, where the vibration amplitude was $\pm 3.0G_x$ the 11 Hertz component was only $\pm 1.65G_x$.)

generated in conjunction with a hydraulically produced vibration. Figure 210 indicates the power density spectrum of the vibration input acceleration. It is noted from this figure that the frequencies of 11, 33 and 55 Hertz accounted for 95 percent of the total power.

The dials tested and the performance measures used were the same as those reported for the previous Taub (Ref. 327) study. The dials were tested at a viewing distance of 21 inches with an ambient illumination at the dials of 34 Ft. Candles. At this viewing distance the "easy" dial graduation markers subtended a visual angle of 144.98 minutes of arc and the scale units 29

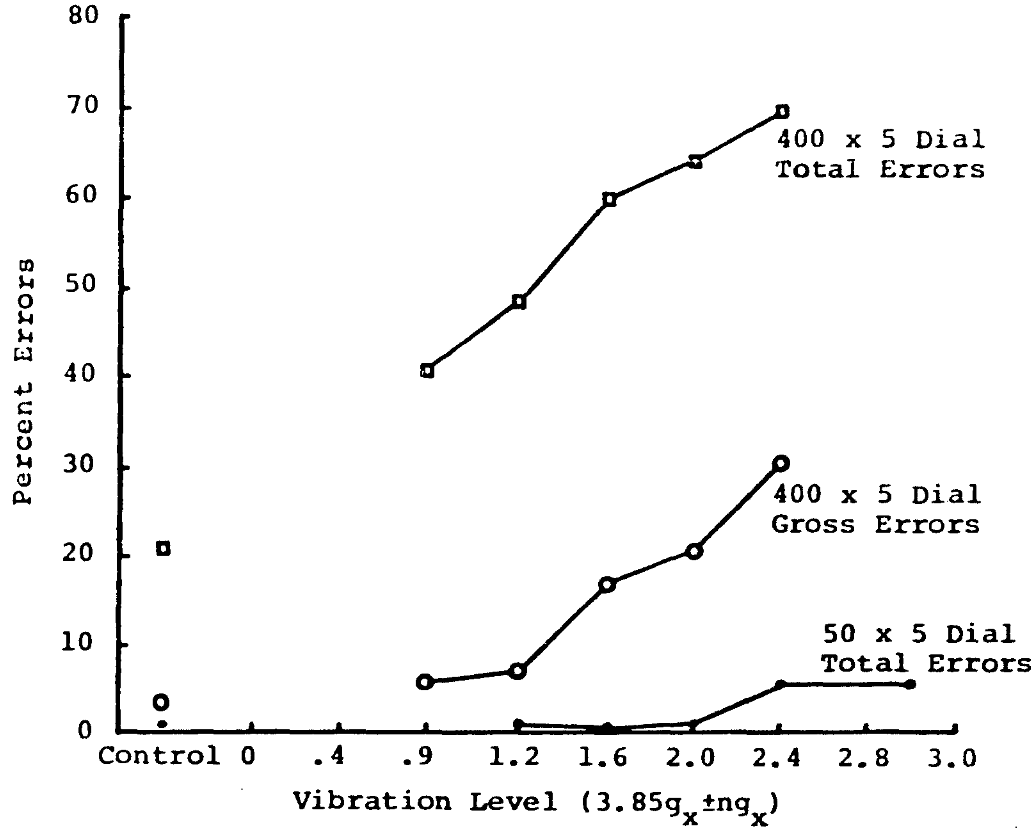


Figure 211. Summary of Mean Error Scores as a Function of the Experimental Conditions.

minutes of arc; the "difficult" dial subtended 18.1 minutes of arc for the graduation markers and 3.63 minutes for the scale units. Five vibration conditions were tested for each of the two dials. The vibration levels (combined in each case with the 3.85 Gx bias) were $\pm 1.2g_x$, $\pm 1.6g_x$, $\pm 2.0g_x$, and $\pm 3.0g_x$ for the easy dial (50 by 5) and $\pm 0.8g_x$, $\pm 1.2g_x$, $\pm 1.6g_x$, $\pm 2.0g_x$, and $\pm 2.4g_x$ for the difficult dial (400 x 5). Only three of these conditions overlap for comparing performance on the two dial tasks. The dials were tested at a viewing distance of 21 inches, with an ambient illumination at the dials of 34 Ft. Candles.

Following three days of practice, 6 subjects were tested on each of the vibration conditions. Figure 211 presents the dial reading data for each of the vibration conditions and the control condition (no vibration). It is immediately obvious that there is a large difference in total errors for the two dial tasks, and that, generally speaking, increasing the amplitude of vibration produced corresponding increases in both total and

gross errors for the difficult dial tasks and no effect for total errors with the easy dial (total and gross errors were computed in the same manner as in the preceding Taub study). No effect on performance was noted for gross errors on the difficult dial until the $\pm 1.6g_x$ vibration condition was encountered.

No statistical analysis of the data was performed for the easy dial due to the small number of performance errors obtained for this condition. For the difficult dial the $\pm 1.6g_x$ ($P<.05$), $\pm 2.0g_x$ ($P<.01$) and $\pm 2.4g_x$ ($P<.01$) vibration levels produced significantly more performance errors than the control condition.

Initially, the intention of this study was to make comparisons with the previous Taub (Ref. 327) study for the 11 Hertz and $\pm 1.2g_x$ and $\pm 2.0g_x$ vibrations conditions. Unfortunately, however, the approximately 50 percent distortion (see Figure 210) of the 11 Hertz vibration and various methodological problems for this study sufficiently altered the independent conditions to make such a comparison unrealistic. These same limitations also restrict any true quantitative evaluation of the results, although it appears that in a strictly qualitative sense, dial reading errors were inversely related to the arc length of the interval between dials and directly related to the amplitude of vibration.

ACCELERATION

Introduction

> "With the development of high-speed airplanes, the problem of the effects on the individual of forces associated with extreme acceleration have become increasingly important. These effects range from impairment of vision and motor abilities to unconsciousness and damage to body structure" (Ref. 331).

Vision, in particular, in comparison to other sense modalities, is affected by acceleration, and should be considered separately from the larger topic of acceleration effects on human performance when evaluating the primarily visual electronic display interface (Ref. 50). The literature on the effects of acceleration on vision can be summarized under two major headings. The first of these covers the subjective reports of the gross effects of acceleration. The second covers the results of the use of objective measures to determine the effect of acceleration on visual parameters such as visual grayout or blackout, visual fields, dial reading, brightness discrimination thresholds and visual acuity. Studies using objective measurements of the degradation in these visual parameters introduced by various configurations of acceleration will be the primary data source for meeting the expressed objective of developing qualitative design guidelines.

Visual Grayout or Blackout

Grayout and blackout are two of the principal effects produced by higher levels of acceleration. Cochran et al. (Ref. 76) established thresholds on 1,000 subjects exposed to positive acceleration (Table 113).

Table 113. Thresholds for Positive Acceleration. (Adapted from Ref. 76)

Criterion	Mean Threshold (g)	Standard Deviation (g)	Range (g)
Loss of Peripheral Vision	4.1	±0.7	2.2 - 7.1
Blackout	4.7	±0.8	2.7 - 7.8
Unconsciousness	5.4	±0.9	3.0 - 8.4

Visual Fields

White and Monty (Ref. 350) report that at 4.4g (range of 3g to 6.5g) the visual field is narrowed to an arc of less than 46^{o}.

Reaction Time

The reaction time studies are not reviewed here for two reasons. First, reaction time does not truly meet the expressed objective of this review, which is to present design-oriented data on the acceleration produced degradation in visual parameters. And secondly, the results for reaction time studies are contradictory, inconsistent and generally not resolved into consistent design-oriented data. Brown (Ref. 47) states,

> "there is wide variability in the effect of acceleration on reaction time, and it seems reasonable to believe there is an actual increase. The discrepancies in results may well be related to different interpretations on the part of different investigators."

Dial Reading

White and Riley (Ref. 351) performed a study to determine if a pilot's ability to read aircraft instrument dials at various brightness levels is impaired by an accelerative force less than that required to produce temporary blindness. Using

the Wright Air Development Center human centrifuge, these authors examined instrument reading performance using apparatus and procedures developed by Chalmers, Goldstein and Kappauf (Ref. 61). This involved the examination of two types of dials, both with a range of 0 to 100 over the full dial circumference. One dial type was graduated in units of one and the other type dial in units of five. Six visually screened (20/20 or better uncorrected visual acuity in both eyes) subjects wearing csu-3/p anti-g suits viewed these dials at a 28 inch viewing distance with illumination levels of .42, 4.2, .42, and 0.004 millilamberts and accelerations of 0 (stationary centrifuge), 1, 2, 3 and 4 gs.

Figure 212 presents percent reading error for the above conditions. The reading error percentages presented in this figure are calculated where all errors are equal regardless of magnitude (an error of one unit in reading counted as much as an error of ten units). These data indicate that at the highest luminance level there are no differences in percentage of errors for the acceleration conditions tested. For the three highest illumination levels and accelerations up to 3 g, there were no significant differences in the percentage of errors. At the two lower luminance levels, errors are inversely related to acceleration. Errors increased systematically with decreasing luminance at the 4 g acceleration. No performance difference existed between the static, 1 and 2 g acceleration conditions. Also, no reading error performance difference existed between the dials graduated in units and the dials graduated in fives.

White and Riley report that their findings are substantially in agreement with Warrick and Lund's (Ref. 341) earlier study on the effects of moderate levels of acceleration on the ability to read instrument dials. Warrick and Lund found that dial reading errors increased from 18 percent at 1.5 g to 24 percent at 3 g. Illumination levels and control conditions were not reported in this study, so useful comparisons with the White and Riley results are not possible. However, both of these investigations determined that impairment of instrument reading ability occur with positive g prior to acceleration induced blackout.

Brightness Discrimination Thresholds

Acceleration can interfere with optical imagery, reduce the oxygen content of the blood, and interfere with blood flow to the eyes (Ref. 346). Braunstein and White (Ref. 44) performed a study to examine the effects these physiological stresses would have on a fundamental test of visual functioning such as brightness discrimination. Five subjects wearing g-suits monocularly viewed an achromatic circular target and background at a 28 inch viewing distance. The target subtended a visual angle of 1^{o} 28' and the background 8^{o} 4'. Brightness discrimination thresholds were determined for positive acceleration levels of 1, 2, 3 and 5 g, and background luminances of 0.03, 0.29, 2.9 and 31.2 Ft. Lamberts.

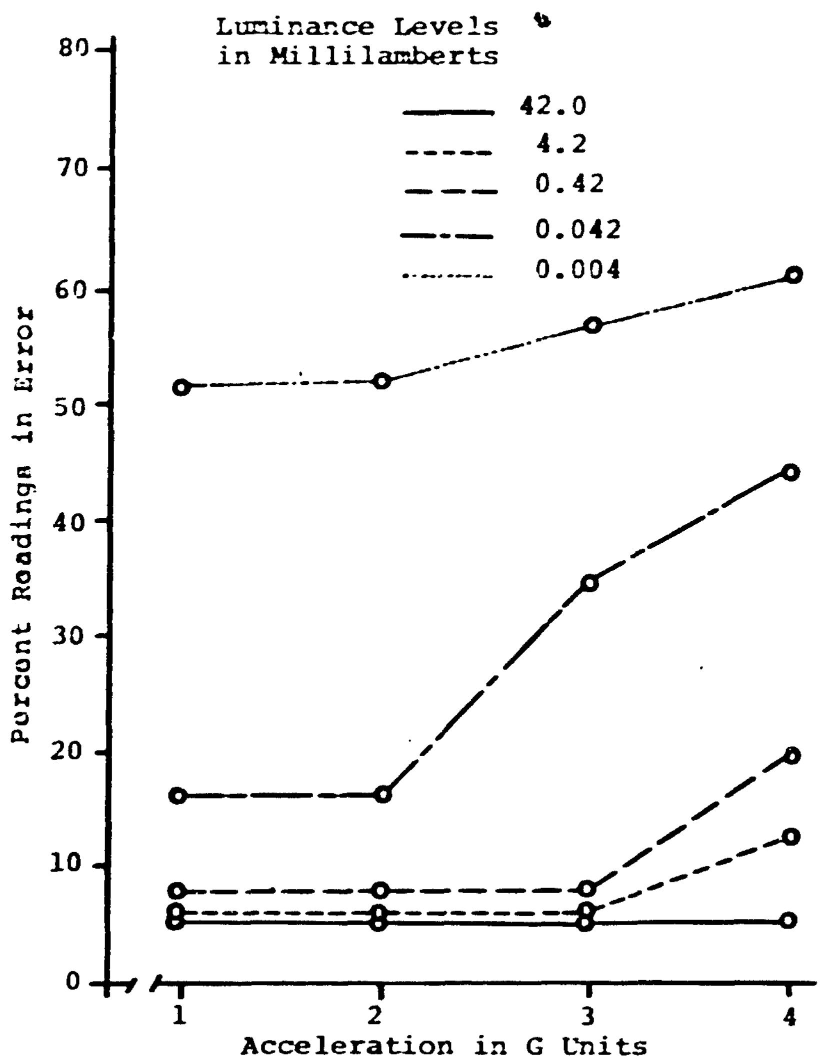


Figure 212. Reading Errors as a Function of Acceleration and Luminance Levels. (Adapted from Ref. 351)

Figure 213 presents the brightness discrimination thresholds in percent contrast for the positive acceleration and illumination levels tested. These data indicate that, in general, an increase in contrast is required to detect the target with increased acceleration. The dimmest background luminance of 0.03 Ft. Lamberts required the greatest increase. At this level, 15.6 percent contrast was required to detect the target at 5 g as compared to 9.4 percent at 1 g. At the brightest background luminance of 31.2 Ft. Lamberts, the 5 g acceleration condition required 5.8 percent contrast while the 1 g level required 2.8 percent contrast. Thus, the brighter background luminance required the smaller increase in percent contrast to maintain threshold. The following conclusion was presented in this report, and appears to develop a reasonable approach for making brightness discriminations under conditions of increasing positive acceleration:

> "Displays requiring the detection of an increment in brightness, such as radar CRT displays, which are adequate in the normal gravitational environment, may prove inadequate when the observer is subjected to gravitational stress. Alteration of either of two parameters of such displays may eliminate this difficulty. A generally brighter display, with targets of the same contrast (percentage of increased brightness) will show greater resistance to the effects of acceleration. Increased target contrast will also overcome the effects of acceleration, for the same background brightness (Ref. 44)."

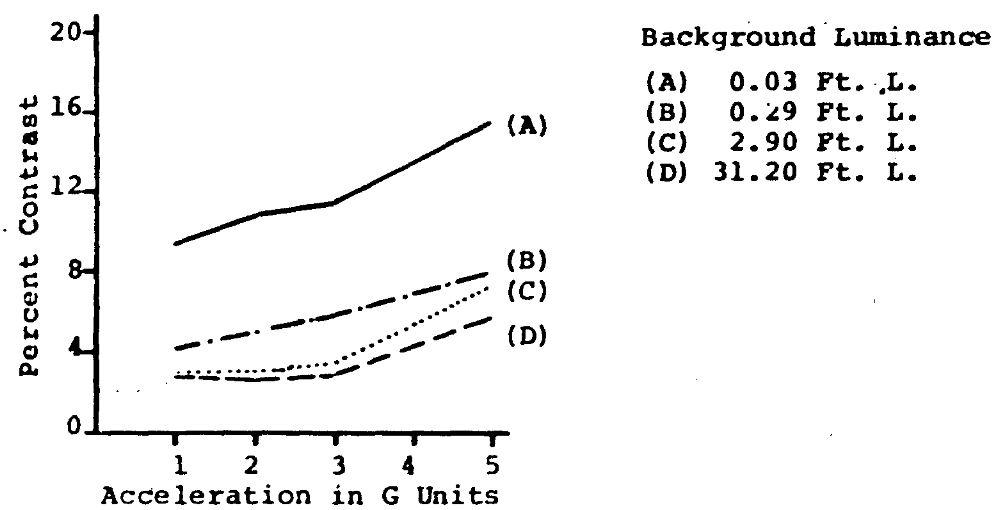


Figure 213. Relationship of Brightness Discrimination Threshold to Level of Positive Acceleration for Four Background Luminance Levels. (Adapted from Ref. 44)

Visual Acuity

Vision is the sense most obviously affected by acceleration; excessive acceleration can cause visual blackout and even unconsciousness. Before these more dramatic changes occur, however, a number of more subtle changes occur characterized by raised thresholds and the limitation of acuity, first peripherally, and then centrally. These visual effects arise not only because of the extent and duration of the acceleration, but also because of the rate at which it is applied. Smedal et al. (Ref. 313) demonstrated that blackout occurs at 3.7 g if a centrifuge is accelerated quickly, whereas moderate acceleration resulted in blackout at approximately 5.6 g's.

The degradation of visual acuity occurs first in the peripheral portion of the eye, gradually extending with increasing acceleration to the central portion of the eye. Mercier, et al. (Ref. 236) suggest that the final part of the visual field to be lost is the area included between the fixation point and the blind spot. He attributes the last effect to the anatomical distribution of the retinal arteries.

Riley and White (Ref. 277) examined the effect of panel brightness on this loss of acuity. They used accelerations of 2 to 5 g's and maximum panel brightness of 42 millilamberts and found that: (1) at maximum luminance levels, the twelve subjects produced few errors up to approximately 3 g, (2) at the lower luminance levels, the error rate increased in proportion to the level of g, but in an inverse proportion to the luminance level (greater degradation at smaller luminance levels, and less degradation at higher luminance levels), (3) four g's resulted in a systematic increase in error rate at all luminance levels. It is apparent from this study that reading errors are a function of both the luminance of the display and the level of acceleration.

In a series of experiments, White and Jorve (Ref. 349) attempted to describe the relationship between visual acuity and acceleration (positive and negative acceleration). In an effort to reduce the effect of reduced cerebral circulation, the body positions for the six subjects were systematically varied. This variation in body position also allowed for the examination of the mechanical effects of acceleration on the eyeball.

Their data indicate that visual acuity decreased progressively as the intensity of the accelerating force was increased above 1 g. The data for both the positive and negative acceleration are plotted in Figure 214. The results were interpreted by White and Jorve to indicate that the crystalline lenses of the eye were displaced in the direction of the accelerating vector. They suggest that at 7 g, the size of the target must be twice that of 1 g if it is to be seen at all.

White (Ref. 348) reported a study by White and Pelder which examined the effects of positive acceleration on the interaction of visual acuity and luminance levels. Under the acceleration stress of 1 g, the expected decrease in visual threshold with increased illumination was found. Repeating the above measurement for the same five subjects under 3 g and again under 4 g stress, the following relationships were found to hold: (1) Acceleration had a significant and progressive effect on visual acuity at all luminance levels. This effect was most noticeable at low luminous levels. (2) At a luminance of 0.01 mL, the minimum angle increased from 4.0 minutes of arc at 1 g to 7.59 minutes of arc under 4 g stress. (3) At a luminance level of 150 mL, the change in visual angle between 1 and 4 g was 0.25 minutes of arc.

Conclusions

Acceleration degrades observer visual performance, and the extent of the degradation is a function of the magnitude luminance level of the display during acceleration. At lower luminance levels (0.01 to approximately 100 mL) acuity

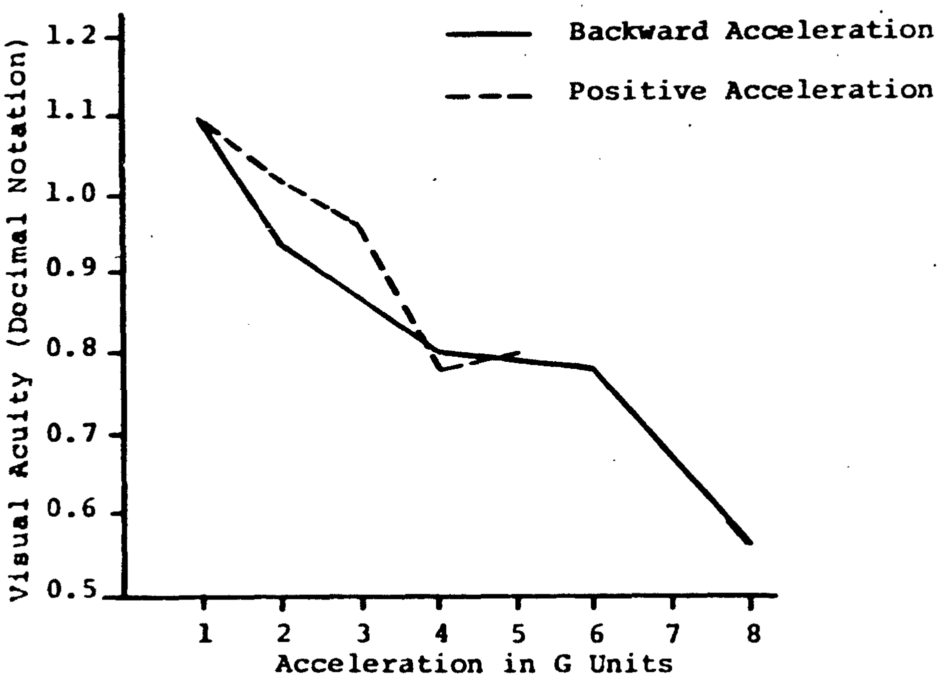


Figure 214. Visual Acuity as a Function of Acceleration. (Adapted from Ref. 349)

degradation is progressively worse with increasing acceleration. At higher luminance levels, the degradation is present, but less significant until the stress reaches 4 g's, at which point acuity deteriorates rapidly, regardless of the luminance level.

RESEARCH RECOMMENDATIONS

Ambient Illumination

Available measurements of atmospheric ambient illumination have fairly well established that maximum illuminance on earth from the sun is approximately 11,000 Ft. Candles. Additionally, selected measurements of sky, cloud and horizon luminances are available, but the degree of consistency among the measurements appears to suffer due to frequent failure to specify environmental conditions prevailing while the measurements were made. Finally, no photometric measurements were found which established luminance levels for the tops of clouds viewed from above at various times of day. Similarly, no data were reviewed which would allow for the development of relative frequency distributions relating the percent of the daytime period during which various ambient illumination levels are observed as a function of selected environmental atmospheric conditions.

Prior to undertaking direct photometric measurements, it is recommended that the relevant literature associated with the field of astronomy should be reviewed with the objective of obtaining the type of luminance data discussed above. Luminance data should be obtained for the mid-summer season and should cover the following conditions: Altitude from sea level to 100,000 feet; time of day from first light to last light; clear sky positions from horizon to horizon throughout a 360 degree heading range; and overcast conditions including measurements made above and below the overcast as well as in the overcast. For each of the above conditions, appropriate sampling of each range must be considered in a practical sense. It would also appear highly desirable to locate or develop a mathematical model for determining ambient illumination levels. If it is found that such data and models do not exist in the astronomy literature, it is recommended that direct photometric measurements be made. Such data, used in conjunction with design data relating to display location and cockpit geometry, would allow for accurate determinations of illuminance levels incident upon electronic display faces as well as the time durations of time during which the various luminance levels could be anticipated.

Vibration

All pilots flying aircraft are exposed to some degree of vibration. In some aircraft the effects of this vibration are negligible; in others, vibration is cited as the major limiting

factor in vehicle systems performance (Ref. 170). Vibration has become a subject of great concern because of the increasing number of low altitude, high speed aircraft such as helicopters and terrain avoiding fighter-bombers. These aircraft are known to produce ride environments which expose their crews to oscillations from the propulsion system, airframe structural flexibility, and aerodynamic gusts (Ref. 173). Hornick (Ref. 173) reported that vibration for these low altitude high speed aircraft is likely to be random in frequency and amplitude with an anticipated peak energy expected for frequencies around 1, 3, 6 and 10 Hertz. The range of 10 to 30 Hertz has been reported by Ketchel et al. (Ref. 205) to be the most detrimental to visual performance, although frequencies above and below this band can cause decrements.

It is recommended that primary consideration be given to vibration imposed on subjects which are normally seated and restrained for the aircraft being considered. Vibration parameters tested should include a frequency range from 3 to 35 Hertz and magnitudes from a minimum of .3 g to a maximum of 3 g. Visual performance tasks under environmental vibration conditions should include legibility tests of electronically generated symbology, alphanumerics, scales and brightness discrimination. Each of these tasks should be tested under a variety of brightness, contrast and symbol characteristics (see research requirements for sections of these same names for ranges of the variables to be tested under vibration conditions).

<u>Acceleration</u>

> "Engineering advances during recent years have made possible aircraft that can withstand tremendous structural strains over long periods of time (minutes), but under such tension the performance of their human operators may be handicapped by gross disturbances of circulation, vision and consciousness (Ref. 349)."

No operationally acceptable research relating the degradation in electronic display legibility to conditions of acceleration is currently available in the literature. The previous section presented evidence which relates conditions of acceleration to various basic psychological and non-electronic display performance data. Test parameters used in these studies indicate that acceleration levels between 1 and 5 g's would be appropriate for preliminary electronic flight display performance tests. This range of acceleration should be investigated for the following: symbol legibility, scale legibility, brightness discrimination, visual acuity and hue discrimination. Each of the above should be tested under a variety of brightness, contrast and resolution conditions. See appropriate sections of this report for ranges of these variables.

REFERENCES

1. Addis, L.K., Wierenga, B.J., and Blanchard, C.E. Design Fabrication of an Experimental Electroluminescent Display Panel. AFFDL-TR-69-106, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, January 1970.

2. Ailslieger, R.E. and Dick, D. "Influence of an Intermittent Visual Stimulation on Perceptual Motor Skills in Aviation." Human Factors, Volume 8, Number 6, Pages 569-572, December 1966.

3. Alexander, H.S. and Chiles, W.D. An Exploratory Study of Prolonged Intermittent Photic Stimulation. WADC-Technical Report No. 59-715, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, November 1959.

4. Allen, M.J. A Study of Visual Performance Using Opthalmic Filters. ASD TR 61-576 (AD 273 230), United States Air Force Life Support Systems Laboratory, Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, October 1961.

5. Alluisi, E.A. and Muller, P.F., Jr. "Verbal and Motor Responses to Seven Symbolic Visual Codes: A Study of S-R Compatability." Journal of Experimental Psychology, Volume 55, Pages 247-254, 1958.

6. Alpern, M. "Metacontrast." Journal of the Optical Society of America, Volume 43, Number 8, Pages 648-657, 1953.

7. Anderson, C.D. Preliminary Report (Personal Communication), August 18, 1970.

8. Anderson, D.A., Huntington, J., and Simonson, E. "Critical Fusion Frequency as a Function of Exposure Time." Journal of the Optical Society of America, Volume 56, Number 11, Pages 1607-1611, November 1966.

9. Anderson, N.S. and Fitts, P.M. "Amount of Information Gained During Brief Exposures of Numerals and Colors." Journal of Experimental Psychology, Volume 56, Number 4, Pages 367-369, 1958.

10. Atkinson, W.H., Crumley, L.M., and Willis, M.P. A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels, V: The Comparative Legibility of Three Fonts for Numerals. Report TED No. NAMEL-609, Aeronautical Medical Equipment Laboratory, Naval Air Material Center, U.S. Naval Base, Philadelphia, Pa., June 1952.

11. Attneave, F. "Physical Determinants of Judged Complexity of Shapes," Journal of Experimental Psychology, Volume 53, Number 4, Pages 221-227, 1957.

12. Baker, C.D. and Grether, W.F. Visual Presentation of Information. WADC Technical Report 54-160 (AD 43 064), Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, August 1954.

13. Baker, C.A., Morris, D.F., and Steedman, W.C. Target Recognition on Complex Displays. Technical Report 59-418, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1959.

14. Baker, C.A. and Nicholson, R.M. "Raster Scan Parameters and Target Identification," Proceedings of 19th Annual Aerospace Electronics Conference, May 1967.

15. Baker, C.H. and Earl, W.K. Visual Detection of Positive Versus Negative Pips on a Radar PPI. Technical Memorandum 750-1 (AD 666 577), Engineering Psychology Branch, Psychological Sciences Division, Office of Naval Research, February 1968.

16. Barmack, J.E. and Sinaiko, J. Human Factors Problems in Computer-Generated Graphic Displays. Institute for Defense Analysis, Report S-234 (AD 636 170), Institute for Defense Analysis, Research and Engineering Support Division, April 1966.

17. Bartley, S.H. "Some Factors Influencing Critical Flicker Frequency." Journal of Psychology, Volume 46, Pages 107-116, 1958.

18. Bartley, S.H. "Subjective Flicker Rate with Relation to Critical Flicker Frequency." Journal of Experimental Psychology, Volume 22, Pages 388-394, 1938.

19. Bartley, S.H. "The Psychophysiology of Vision." In Stevens, S.S. (Ed.) Handbook of Experimental Psychology, Pages 921-984, John Wiley, New York, 1941.

20. Bartley, S.H. Vision: A Study of its Basis. Hefner Publishing Company, New York, 1963.

21. Bartley, S.H. and Nelson, T.M. "A Further Study of Pulse-to-Cycle Fraction and Critical Flicker Frequency: A Decisive Theoretical Test." Journal of the Optical Society of America, Volume 51, Number 1, Pages 41-49, 1961.

22. Batterby, W.S. and Jaffe, R. "Temporal Factors Influencing the Perception of Visual Flicker." Journal of Experimental Psychology, Volume 46, Number 3, Pages 154-159, 1953.

23. Battig, W.F., Vos, J.F., and Brogden, W.J. "Effect of Frequency of Target Intermittence on Tracking." Journal of Experimental Psychology, Volume 49, Number 4, Pages 244-248, 1955.

24. Belcher, J.J. Increasing Legibility in Electroluminescent Alphanumeric Displays. RCA-TR-60-582-7, cited in S.D. Stephenson and R.J. Scheffer, The Relative Legibility of Five Different Segmented Electroluminescent Fonts, RADC-TR-68-372, Rome Air Development Center, Griffis Air Force Base, New York, 1968.

25. Bell, G.L. Studies of Display Symbol Legibility. XVI: The Legibility of Teletypewriter Symbols on Television. ESD-TR-67-104 (AD 655 356), Command Systems Computer and Display Division, Electronic Systems Division, Air Force Systems Command, U.S. Air Force, Hanscom Field, Mass., April 1967.

26. Benjamin, M.E. "F-14 Uses Digital Display Method." Aviation Week and Space Technology, Volume 93, Number 3, Pages 45-46, July 1970.

27. Bennett, C.A., Winterstein, S.H., and Kent, R.E. "Image Quality and Target Recognition." Human Factors, Volume 9, Number 1, Pages 5-32, February 1967.

28. Bergum, B.O. and Burrell, W.E. Consulting Report Symbol-Confusion in Fire Detection Systems. HRRO-CR, U.S. Army Air Defense, Human Research Unit, Fort Bliss, Texas, 1964.

29. Biberman, L.M. The Inappropriateness of Commercial Television Standards for Military Night Operations. Research Paper Number P-235 (AD 479 583), Institute for Defense Analysis, Research and Engineering Support Division, January 1966.

30. Bishop, H.P. and Crook, M.N. Absolute Identification of Color for Targets Presented Against White and Colored Backgrounds. WADC Technical Report 60-611 (AD 266 403), Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1961.

31. Bitterman, M.E. and Krauskopf, J. Some Determinants of Threshold for Visual Form. WADC Technical Report 53-311 (AD 23 337), Aero Medical Laboratory, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, September 1953.

32. Blackwell, H.R. "Contrast Thresholds of the Human Eye." Journal of the Optical Society of America, Volume 36, Number 11, Pages 624-643, 1946.

33. Blondel, A. and Rey, J. "The Perception of Lights of Short Duration at their Range Limits." Transactions of the Illumination Engineering Society, Volume 7, Pages 625-658, 1912.

34. Boettner, E.A. and Wolter, J.R. Transmission of the Ocular Media. Technical Documentary Report Number MRL-TDR-62-34, Life Support Systems Laboratory, 6570th Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, May 1962.

35. Botha, B. and Shurtleff, D. Studies of Display Legibility, II: The Effects of Line Construction, Exposure Time, and Stroke Width. ESD-TDR-63-249 (AD 414 323), Operational Applications Laboratory, Electronic Systems Division, Air Force Systems Command, U.S. Air Force, Hanscom Field, Mass., July, 1963.

36. Botha, B. and Shurtleff, D. Studies in Display Symbol Legibility: Part II. The Effects of the Ratio of Widths of Inactive to Active Elements Within a TV Scan Line and the Scan Pattern Used in Symbol Construction. ESD-TDR-63-440 (AD 420 010), United States Air Force, Electronic Systems Division, Air Force Systems Command, U.S. Air Force, Hanscom Field, Mass., September 1963.

37. Brown, F.R. A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels, IV: Legibility of Uniform Stroke Capital Letters as Determined by Size and Height to Width Ratio and as Compared to Garamond Bold." Report TED No. NAMEL-609, Naval Air Material Center, Philadelphia, Pa., March 1953.

38. Bowen, H.M., Andreassi, J., Traux, S., and Orlansky, J. Optimum Symbols for Radar Displays. Office of Naval Research Contract Number 2682(00) (AD 227 014), Office of Naval Research, Washington, D.C., September 1959.

39. Boynton, R.M. "Theory of Color Vision." Journal of the Optical Society of America, Volume 50, Number 10, Pages 929-944, October 1960.

40. Brainard, R.C., Mounts, F.W. and Prasada, B. "Low-Resolution TV: Subjective Effects of Frame Repetition and Picture Replenishment." Bell System Technical Journal, Volume 66, Number 5, Pages 233-260, 1962.

41. Brainard, R.W. and Caum, K.B. Evaluation of an Image Quality Enhancement Technique. AMRL-TR-65-143 (AD 624 470), Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, September 1965.

42. Brainard, R.W., Hanford, E.C., and Marshall, R.H. Resolution Requirements for Identification of Targets in Television Imagery. NA63H-794, North American Aviation, Inc., Columbus, Ohio, January 1965.

43. Brainard, R.W. and Ornstein, G.N. Image Quality Enhancement. AMRL-TR-65-28 (AD 616 895), Behavioral Science Laboratory, Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, April 1965.

44. Braunstein, M.L. and White, W.J. The Effects of Acceleration on Visual Brightness Discrimination. Contract Number Nonr-3457(00) (AD 269 380), Physiological Psychology Branch, Office of Naval Research, Washington, D.C., December 1961.

45. Brown, F.R. and Lowery, E.A. The Study of the Requirements for Letters, Numbers and Markings to be Used on Trans-Illuminated Aircraft Control Panels, I: The Effect of Stroke Width Upon the Legibility of Capital Letters. TED No. NAMEL-609, (ATI 205 706), Naval Air Material Center, Philadelphia, Pa., September 1949.

46. Brown, F.R., Lowery, E.A., and Willis, M.P. A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels, III: The Effect of Stroke Width and Form Upon the Legibility of Numbers. Report TDD No. NAMEL-609, (ATI 107 638), Aeronautical Medical Equipment Laboratory, Naval Air Experimental Station, Naval Air Material Center, Philadelphia, Pa., May 1961.

47. Brown, J.L. "Acceleration and Human Performance." In Sinaiko, H.N. (Ed.), Selected Papers on Human Factors in the Design and Use of Control Systems, Dover Publication Company, Inc., New York, 1961.

48. Brown, J.L. "Flicker and Intermittent Stimulation." In Graham, C.H. (Ed.), Vision and Visual Perception, Wiley and Sons, New York, 1965.

49. Brown, J.L. "Low-Resolution T.V.: Subjective Comparison of Interlaced and Non-Interlaced Pictures." Bell System Technical Journal, Volume 66, Pages 199-232, 1967.

50. Brown, J.L. and Lechner, M. "Acceleration and Human Performance." Journal of Aviation Medicine, Volume 27, Pages 32-49, 1956.

51. Bruns, R.A. and Miller, P.L. Light Transmission Characteristics of Three Wire Mesh Filters for Radar Display. Technical Memorandum TW-69-24 (AD 851 654), U.S. Navy Missile Center, Point Mugu, Calif., May 1969.

52. Bryam, G.M. "The Physical and Photochemical Basis of Visual Resolving Power. I. The Distribution of Illumination in Retinal Images." Journal of the Optical Society of America, Volume 34, Number 10, Pages 571-591, 1944.

53. Bryden, J.E. "Design Considerations for Computer Driven CRT Displays." Computer Design, Pages 38-46, March 1969.

54. Bryden, J.E. "Some Notes on Measuring Performance of Phosphors Used in CRT Displays." Proceedings of the 7th National Symposium, Society for Information Display, Boston, Mass., October 1966.

55. Burnham, R.W., Hanes, R.M. and Bartleson, C.J. Color: A Guide to Basic Facts and Concepts. John Wiley and Sons, New York, 1967.

56. Cambell, F.W. and Green, D.G. "Optical and Retinal Factors Affecting Visual Resolution." Journal of Physiology (London), Volume 176, Pages 576-593, 1965.

57. Carel, W.L. Analysis of Pictorial Displays. Third Quarterly Progress Report (AD 613 274), Joint Army-Navy Aircraft Instrumentation Research, Office of Naval Research, March 1965.

58. Carel, W.L. Pictorial Displays for Flight. Office of Naval Research Contract Number NONR 4468(00) (AD 637 669), Office of Naval Research, December 1965.

59. Carr, W.J. and Garner, W.R. "The Maximum Precision of Reading Fine Scales." Journal of Psychology, Volume 34, Pages 85-94, 1952.

60. Casperson, R.C. "The Visual Discrimination of Geometric Forms." Journal of Experimental Psychology, Volume 40, Pages 668-681, 1950.

61. Chalmers, E.L., Goldstein, M., and Kappauf, W.E. The Effect of Illumination on Dial Reading - and Appendix. AF Technical Report No. 6021 (ATI 84 004), United States Air Force, Air Material Command, Wright-Patterson Air Force Base, Ohio, August 1950.

62. Chapanis, A. How We See: A Summary of Basic Principles. NAVTRADEVCEN 166-I-85 (AD 204 769), U.S. Naval Training Device Center, Port Washington, New York, 1949.

63. Chapanis, A. and Halsey, Rita M. "Absolute Judgements of Spectrum Colors." The Journal of Psychology, Volume 42, Pages 99-103, 1956.

64. Chapanis, A. and Scarpa, L.C. "Readability of Dials at Different Distances with Constant Visual Angle." Human Factors, Volume 9, Number 5, Pages 419-425, 1967.

65. Christensen, J.M. Some Typical Sky and Earth Brightnesses at Altitudes 10,000 to 40,000 Feet and Their Relationship to the Eye-Adaptation Problems of the Radar Operator. Report Number TSEAA-694-11 (AD 494 855), Army Air Forces, Air Materiel Command, Aero Medical Laboratory, Wright-Patterson Air Force Base, Ohio, December 1946.

66. Christensen, J.M. Quantitative Instrument Reading as a Function of Dial Design, Exposure Time, Preparatory Fixation, and Practice. WADC TR 52-116 (AD 101), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, September 1952.

67. Christensen, J.M. The Importance of Certain Dial Design Variables in Quantitative Instrument Reading. WADC TR 55-376 (AD 97 492), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1955.

68. Churchill, A.V. "The Effect of Scale Interval Length and Pointer Clearance on Speed and Accuracy of Interpolation." Journal of Applied Psychology, Volume 40, Number 6, Pages 358-361, 1956.

69. Churchill, A.V. "Optimal Interval Length for Visual Interpolation: The Effect of Viewing Distance." Journal of Applied Psychology, Volume 43, Number 2, Pages 125-128, 1959.

70. Churchill, A.V. and Allan, D.G. Experimental Dial Design. DRML Report No. 164-1 (AD 414 313), Defense Research Medical Laboratories, Defense Research Board, Department of National Defense, Toronto, Ontario, Canada, March 1955.

71. Ciuffini, A.J. and Rizy, E.F. High Contrast Versus Standard Electroluminescent Panels on the Identification of Symbology. RADC-TR-66-271 (AD 484 731), United States Air Force, Rome Air Development Center, Griffiss Air Force Base, New York, June 1966.

72. Clarke, N.P., Taub, H., Scherer, H.F., Temple, W.F., Vykukal, H.E., and Matter, M. Preliminary Study of Dial Reading Performance During Sustained Acceleration and Vibration. AMRL-TR-65-110 (AD 622 298), Aero Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, August 1965.

73. Cobb, P.W. The Effects on Foveal Vision of the Bright Surround." Psychological Review, Volume 20, Pages 23-32, 1914.

74. Cobb, P.W. and Geissler, L.R. "The Effects on Foveal Vision of Bright Surround." Psychological Review, Volume 20, Pages 425-447, 1913.

75. Cobb, P.W. and Moss, R.K. "The Four Variables of Visual Threshold." Journal of the Franklin Institute, Volume 205, Pages 831-847, 1928.

76. Cochran, L., Gard, P., and Norsworthy, M. Variations in Human G Tolerance to Positive Acceleration. Report No. NM001 059.02.10 (AD 50 297), U. S. Naval School of Aviation Medicine, Naval Air Station, Pensicola, Florida, August 1954.

77. Coermann, R. "Effect of Vibration and Noise on the Human Organism." RAE Transactions, Number 121 (M.O.S.), 1946.

78. Coermann, R.R., Magid, E.B., and Lange, K.O. "Human Performance Under Vibrational Stress." Human Factors, Volume 4, Number 5, Pages 315-324, 1962.

79. Cohen, J. and Dinnerstein, A. A Comparison of a Linear Scale and Three Logarithmic Scales on the Time for Check Reading. WADC TR 57-63 (AD 118 017), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1958.

80. Cohen, J. and Dinnerstein, A.J. Flash Rate as a Visual Coding Dimension for Information. WADC Technical Report 57-64 (AD 118 018), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, May 1958.

81. Cohen, J. and Senders, Virginia L. An Experiment on Dial Coding. WADC Technical Report 52-209, Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, September 1952.

82. Cohen, J. and Senders, V.L. The Effects of Absolute and Conditional Probability Distributions on Instrument Reading: III. A Comparison of a Linear Scale and Two Scales with Expanded Central Portions. WADC TR 57-65 (AD 118 019), United States Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1958.

83. Collier, R.M. "An Experimental Study of form Perception in Indirect Vision." Journal of Comparative Psychology, Volume 11, Number 3, Pages 281-290, 1931.

84. Colman, K.W., Courtney, D., Freeman, J.B., and Bernstein, R. The Control of Specular Reflections from Bright Tube Radar Displays. Courtney and Company Report No. 23 (AD 209 279), Engineering Psychology Branch, Office of Naval Research, Washington, D.C., November 1958.

85. Conover, D.W. The Amount of Information in the Absolute Judgement of Munsell Hues. WADC Technical Note 58-262 (AD 233 445), Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, June 1959.

86. Connor, J.P. and Ganoug, R.E. "An Experimental Determination of the Visual Thresholds at Low Values of Illumination." Journal of the Optical Society of America, Volume 25, Pages 287-294, 1935.

87. Conover, D.W. and Kraft, C.L. The Use of Color in Coding Displays. WADC Technical Report 55-471 (AD 204 214), Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1958.

88. Connor, J.P. and Ganoug, R.E. "An Experimental Determination of the Visual Thresholds at Low Values of Illumination." The Journal of the Opitcal Society of America, Volume 25, Pages 287-294, 1935.

89. Coonan, T.J. and Klemmer, E.T. Reading Linear Scales: The Contribution of Eye Movements to Accuracy. AFCRC Technical Note 56-8 (AD 98 829), Operational Applications Laboratory, Air Force Cambridge Research Center, Air Research and Development Command, Bolling Air Force Base, Washington, D.C., October 1956.

90. Cornog, D.Y. and Rose, F.C. Legibility of Alphanumeric Characters and Other Symbols: Vol. II, A Reference Handbook. NBS Misc. Pub. 262-2, Institute of Applied Technology, National Bureau of Standards, Washington, D.C., 1967.

91. Cornog, D.Y., Rose, F.C., and Walkowicz, J.L. Legibility of Alphanumeric Characters and Other Symbols: Vol. I, A Permuted Title Index and Bibliography. National Bureau of Standards Publication 262-1, Institute of Applied Technology, National Bureau of Standards, Washington, D.C., 1964.

92. Craik, K.J.W. "The Effects of Adaptation Upon Visual Acuity." British Journal of Psychology, Volume 29, Pages 252-266, 1939.

93. Crook, M.N. and Baxter, F.S. The Design of Digits. WADC TR-54-262 (AD 50 080), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, June 1954.

94. Crook, M.N., Bishop, H.P., Fehrer, C.E., and Wade, E.A. Luminance Reintensification at Frequencies from 40 to 300 Cycles Per Second as a Factor in the Reading of Simulated Visual Displays. AFCCDD-TR-61-5 (AD 255 556), Operational Applications Office, Air Force Command and Control Development Division, Air Research and Development Command, United States Air Force, Bedford, Mass., October 1960.

95. Crook, M.N., Hanson, J.A., and Weisz, A. Legibility of Type as a Function of Stroke Width, Letter Width, and Letter Spacing Under Low Illumination. WADC TR-53-440 (AD 56 537), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1954.

96. Crook, M.N., Hanson, J.A., and Weisz, A. Legibility of Type as Determined by the Combined Effect of Typographical Variables and Reflectance of Background. WADC TR-53-411 (AD 43 309), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1954.

97. Cross, K.D. and Bittner, A.C. JANAIR Vertical Contact Analog Display Evaluation Program: Accuracy of Altitude, Roll, Angle, and Pitch Angle Judgements as a Function of Size of Vertical Contact Analog Display. JANAIR Report No. 680713 (AD 683 302), Naval Missile Center, Point Mugu, California, January 1969.

98. D'Aiuto, J.R. "Resolution, Video Bandwidth and Frame Time." Information Display, Volume 6, Number 1, January/February 1969.

99. Dardano, J.F. and Donley, R. Evaluation of Radar Symbols for Target Identification. Technical Memorandum 2-58 (AD 158 180), U.S. Army Human Engineering Laboratories, Aberdeen Proving Grounds, Maryland, March 1958.

100. Dardano, J.F. and Stephens, J.A. Discriminability of AAOC Symbols. Technical Memorandum 4-58 (AD 200 845), Human Engineering Laboratory, Aberdeen Proving Ground, Maryland, 1958.

101. Davis, C.J. Radar Symbology Studies Leading to Standardization: II. Discrimination in Mixed Displays. Technical Memorandum 5-69 (AD 688 125), Human Engineering Laboratoies, Aberdeen Research and Development Center, Aberdeen Proving Grounds, Maryland, March 1969.

102. Davis, S. Computer Data Display. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1969.

103. Debons, A. and Fried, C. Effects of Rate and Prolonged Viewing of Radar Signal Flicker. RADC-TR-58-69 (AD 148 730), Rome Air Development Center, Griffiss Air Force Base, New York, May 1958.

104. Deese, J. Complexity of Contour in the Recognition of Visual Form. Technical Report 56-60 (AD 94 610), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1956.

105. Dennis, J.P. The Effect of Whole Body Vibration on a Visual Performance Task. R:C.E.P.R.G. Report Number 104 (AD 247 249), Clothing and Equipment Physiological Research Establishment, Directorate of Physiological and Biological Research (England), August 1960.

106. Deutsch, S. "Pseudo-Random Dot Scan Television Systems." IEEE Transactions on Broadcasting, Volume BC-11, Pages 11-21, 1965.

107. Drazin, D. "Factors Affecting Vision During Vibration." Research, Volume 15, Pages 275-280, 1962.

108. Duke-Elder, Sir W.S. Text-Book of Opthalmology IV. Henry Kimpton, London, 1949.

109. Dunlap and Associates, Inc. An Investigation of Speed and Accuracy in Reading Multiscale Meters. (AD 236 589), U.S. Army, Signal Research and Development Laboratory, Fort Monmouth, New Jersey, April 1960.

110. Duntley, S.Q., Gordon, H.I., Taylor, J.H., White, C.T., Boileau, A.R., Tyler, H.E., Austin, R.W., and Harris, J.L. "Visibility." Applied Optics, Volume 3, Number 5, Pages 549-598, May 1964.

111. Egli, P.H. High Visibility Display. AFAL-TR-69-136 (AD 852 925), Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio, May 1969.

112. Elias, M.F. The Relation of Symbol Resolution to Recognition of Televised Symbols. Tri-National Symposium of Information Presentation, May 1965.

113. Elias, M.F. Speed of Identification of Televised Symbols as a Function of Vertical Resolution. RADC-TR-65-239 (AD 619 959), Rome Air Development Center, Griffiss Air Force Base, New York, July 1965.

114. Elias, M.F., Snadowsky, A.M., and Rizy, E.F. The Relation of Number of Scan Lines Per Symbol Height to Recognition of Televised Alphanumerics. RADC-TDR-64-433 (AD 608 789), Rome Air Development Center, Griffiss Air Force Base, New York, October 1964.

115. Elkin, E.H. Effects of Scale Shape, Exposure Time, and Display-Response Complexity on Scale Reading Efficiency. WADC TR 58-472 (AD 209 381), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, February 1959.

116. Eriksen, C.W. "Location of Objects in a Visual Display as a Function of the Number of Dimensions on which the Objects Differ." Journal of Experimental Psychology, Volume 44, Number 1, Pages 56-60, 1952.

117. Erickson, R.S. and Main R.E. Target Acquisition on Television: Preliminary Experiments. NOTS TP 4077, United States Navy, August 1966.

118. Fehrer, E.V. "An Investigation of the Learning of Visually Perceived Forms." American Journal of Psychology, Volume 47, Number 2, Pages 187-221, 1935.

119. Fincham, E.F. "The Accommodation Reflex and Its Stimulus." British Journal of Opthalmology, Volume 35, Pages 381-393, 1951.

120. Fink, D.G. Television Engineering Handbook. McGraw-Hill Book Company, Inc., New York, 1958.

121. Fitts, P.M., Jones, R.E., and Milton, J.L. Eye Fixations of Aircraft Pilots: III. Frequency, Duration and Sequence Fixations When Flying Air Force Ground Controlled Approach System (GCA). USAF Technical Report No. 5967, United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, February 1950.

122. Fitts, P.M., Weinstein, M., Rappaport, M., Anderson, N., and Leonard, J.A. "Stimulus Correlates of Visual Pattern Recognition; A Probability Approach." Journal of Experimental Psychology, Volume 51, Number 1, Pages 1-11, 1956.

123. Foley, P.J. "Evaluation of Angular Digits and Comparisons with a Conventional Set." Journal of Applied Psychology, Volume 40, Number 3, Pages 178-180, 1956.

124. Gainer, C.A., Monroe, R.D., Brown, J.E., Bertone, C.M., Nichols, D.W., Dent, P.L., and Barnebey, S.F. All-Weather Landing Simulation for Category III Airborne Configuration: Volume I. Summary of Studies on Flight Directors and Split Axis Control. FAA SRDS Report No. FD67-56, Systems Research and Development Service, Federal Aviation Agency, Washington, D.C., July 1967.

125. Gainer, C.A. and Obermayer, R.W. "Pilot Eye Fixations While Flying Selected Maneuvers Using Two Instrument Panels." Human Factors, Volume 6, Number 5, Pages 485-501, 1964.

126. Gaito, J. "Visual Discrimination of Straight and Curved Lines." American Journal of Psychology, Volume 72, Pages 236-242, 1959.

127. Gebhard, J.W. Psychological Problems in Coding Information for Visual Displays. Report 166-1-93 (AD 640 077), Office of Naval Research, Special Devices Center, John Hopkins University, Baltimore, Maryland, May 1949.

128. Gebhard, J.W. Target Coding by Means of Visual Flicker. Report 166-1-93 (AD 640 060), Office of Naval Research, Special Devices Center, John Hopkins University, Baltimore, Maryland, October 1948.

129. Geissler, L.R. "Form Perception on Indirect Vision." Psychological Bulletin, Volume 23, Pages 135-136, 1926.

130. Geldard, F.A. The Human Senses. John Wiley and Sons, Inc., New York, 1960.

131. General Electric Company. Visual Factors in the Contact Analog. (AD 263 820), General Electric Company, Advanced Electronics Center, Ithaca, New York, 1961.

132. Gerathewohl, S.J. Conspicuity of Flashing and Steady Light Signals, II. High Contrasts. Project 21-24-014, Report Number 2, School of Aviation Medicine, Randolph Field, Texas, 1952.

133. Gerathewohl, S.J. Investigation of Perceptual Factors Involved in the Interpretation of PPI-Scope Presentations. II. A Pilot Study on Form Discrimination. Report Number 2 (AD 165 550), USAF School of Aviation Medicine, Randolph Field, Texas, August 1952.

134. Gerathewohl, S.J. and Rubinstein, D. Investigation of Perceptual Factors Involved in the Interpretation of PPI Scope Presentations: III. Form Discrimination Under Conditions of Heavy Noise. Project Report 21-24-004, Number 1 (AD 19 692), School of Aviation Medicine, Randolph Air Force Base, Texas, 1953.

135. Gerathewohl, S.J. "Conspicuity of Flashing Signals of Different Frequency and Duration." Journal of Experimental Psychology, Volume 48, Number 4, Pages 247-251, 1954.

136. Getline, G.L. F-106A Environmental Vibration. General Dynamics Corporation Report DP-8-232 (AD 693 873), Convair Division, General Dynamics Corporation, March 1960.

137. Gibbons, K. and Howarth, C.I. "Prediction of the Light-Time Fraction on the Critical Fusion Frequency; An Insight Into Fourier Analysis." Nature, Volume 190, Pages 330-331, 1961.

138. Gibney, T.K. Legibility of Segmented Versus Standard Numerals: A Review. AMRL-TR-67-116, (AD 661 262), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, June 1967.

139. Gibson, K.S. and Tyndall, E.P.T. "The Visibility of Radient Energy." Scientific Paper 19, Number 475, U.S. Bureau of Standards, 1923.

140. Glasford, G.M. Fundamentals of Television Engineering. McGraw-Hill Electrical and Electronic Engineering Series, New York, 1955.

141. Gould, J.D. "Visual Factors in the Design of Computer-Controlled CRT Displays." Human Factors, Volume 10, Number 4, Pages 359-376, August 1968.

142. Gould, J.D. and Makous, W.L. "Vision and Lasers; Human Factors of Laser Displays." Information Displays, Volume 5, Number 6, Pages 25-30, 1968.

143. Graham, C.H. "Visual Perception." In Stevens, S.S. (Ed.), Handbook of Experimental Psychology, Wiley and Sons, New York, 1956.

144. Graham, N.E. "The Speed and Accuracy of Reading Horizontal Vertical and Circular Scales." Journal of Applied Psychology, Volume 40, Number 4, Pages 228-232, 1956.

145. Graham, C.H. (Ed.). Vision and Visual Perception. John Wiley and Sons, Inc., New York, 1965.

146. Granit, R. and Hammond, E.L. "Comparative Studies on the Peripheral and Central Retina. V. The Sensation-Time Curve and the Time Course of the Fusion Frequency of Intermittent Stimulation." American Journal of Psychology, Volume 98, Pages 654-663, 1931.

147. Green, B.F. and Anderson, L.K. "Color Coding in a Visual Search Task." Journal of Experimental Psychology, Volume 51, Number 1, Pages 19-24, 1956.

148. Grether, W.F. The Effect of Variations in Indicator Design Upon Speed and Accuracy of Altitude Readings. Report No. TSEAA 694-14 (ATI 10837), Army Air Force, Air Material Command, Wright-Patterson Air Force Base, Ohio, September 1947.

149. Grether, W.F. "Instrument Reading: I. The Design of Long-Scale Indicators for Speed and Accuracy of Quantitative Reading." Journal of Applied Psychology, Volume 33, Number 3, Pages 363-372, 1949.

150. Grether, W.F. and Williams, A. Speed and Accuracy of Dial Reading as a Function of Dial Diameter and Spacing of Scale Divisions. Report No. TSEAA-694-6 (ATI 27507), United States Air Force, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, March 1947.

151. Guyton, A.C. Textbook of Medical Physiology. Second Edition, W. B. Saunders Company, Philadelphia, 1964.

152. Haig, C. "The Course of Rod Dark Adaptation as Influenced by Intensity and Duration of Pre-adapting to Light." Journal of General Physiology, Volume 24, Pages 735-751, 1941.

153. Haines, R.F. The Effect of High Luminance Sources Upon the Visibility of Point Sources. National Aeronautics and Space Administration TM-X-56561, Ames Research Center, Moffett Field, California, 1965.

154. Hake, H.W. and Garner, W.R. "The Effect of Presenting Various Numbers of Discrete Steps on Scale Reading Accuracy." Journal of Experimental Psychology, Volume 42, Number 5, Pages 358-366, November 1951.

155. Halse, R.M. Character Design in a 5x7 Matrix of Squares. AFCCDD-TN-61-3 (AD 252 030), Operational Applications Office, Directorate of Technology, Air Force Command and Control Development Division, Bedford, Mass., November 1960.

156. Hanes, R.M. "Some Effects of Shape on Apparent Brightness." Journal of Experimental Psychology, Volume 40, Pages 650-654, 1950.

157. Hanes, R.M. and Rhodes, M.V. "Color Identification as a Function of Extended Practice." Journal of the Optical Society of America, Volume 49, Number 11, Pages 1060-1064, 1959.

158. Hanes, R.M. and Williams, S.B. "Visibility on Cathode-Ray Screens: The Effect of Light Adaptation." Journal of the Optical Society of America, Volume 38, Number 4, Pages 363-377, 1948.

159. Harshbarger, J.H. Development of a High Resolution Research Television System. AMRL-TR-65-235, Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, December 1965.

160. Hecht, S., Ross, S., and Mueller, C.G. "The Visibility of Lines and Squares at High Brightnesses." Journal of the Optical Society of America, Volume 37, Number 26, Pages 500-507, 1947.

161. Hecht, S. and Mintz, E.V. "The Visibility of a Single Line at Various Illuminations and the Retinal Basis of Visual Resolution." Journal of General Physiology, Volume 22, Pages 593-612, 1939.

162. Helson, H. and Fehrer, E.V. "The Role of Form in Perception." American Journal of Psychology, Volume 44, Pages 79-102, 1932.

163. Hemingway, J.C. and Erickson, R.A. "Relative Effects of Raster Scan Lines and Image Subtense on Symbol Legibility on Television." Human Factors, Volume 11, Number 4, Pages 331-338, August 1969.

164. Henisch, H.K. Electroluminescence. Peragmon Press, New York, 1962.

165. Helson, H. and Steger, J.A. "On the Inhibitory Effect of the Second Stimulus Following the Primary Stimulus to React." Journal of Experimental Psychology, Volume 64, Number 3, Pages 201-205, 1962.

166. Higgins, G.C. and Jones, L.A. "The Nature and Evaluation of Sharpness of Photographic Images." Journal of the Society of Motion Picture and Television Engineers, Volume 58, Pages 277-290, 1952.

167. Hitt, W.D. "An Evaluation of Five Different Abstract Coding Methods." Human Factors, Volume 3, Number 2, Pages 120-130, July 1961.

168. Hochberg, J.E., Gleitman, H., and Macbride, P.D. "Visual Threshold as a Function of Simplicity of Form." American Psychologist, Volume 3, Pages 341-342, 1948.

169. Holladay, L.L. "The Fundamentals of Glare and Visual Acuity." Journal of the Optical Society of America, Volume 12, Number 4, Pages 271-319, April 1926.

170. Holland, C.L. "Performance Effects of Long-Term Random Vertical Vibration." Human Factors, Volume 9, Number 2, April 1967.

171. Honigfeld, A.R. Radar Symbology: A Literature Review. Technical Memorandum 14-64 (AD 461-180), Human Engineering Laboratories, Aberdeen Proving Ground, Maryland, September 1964.

172. Horn, J.E. and McCutcheon, J.J. "Decay Time of Some Image Tube Phosphors as a Function of Excitation Time." Proceedings of the IEEE, Volume 58, Number 4, Pages 592-593, April 1970.

173. Hornick, R.J. and Lefritz, N.M. "A Study and Review of Human Response to Prolonged Random Vibration." Human Factors, Volume 8, Number 6, Pages 481-482, December 1966.

174. Howell, W.C. and Kraft, D.L. Size, Blur and Contrast as Variables Affecting the Legibility of Alphanumeric Symbols on Radar-Type Displays. WADC-TR-59-536 (AD 232 889), Laboratory of Aviation Psychology, Wright-Patterson Air Force Base, Ohio, September 1959.

175. Humes, J.M. and Bauerschmidt, D.K. Low Light Level T.V. Viewfinder Simulation Program: Phase B. The Effects of Television System Characteristics Upon Operator Target Recognition Performance. Technical Report AFAL-TR-68-271 (AD 849 339), Air Force Avionics Laboratory, Aerospace Medical Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, November 1968.

176. Hyman, C.E. Anti-Glare Coatings for Computer-Controlled CRT's. IBM Technical Note TN 21.575-23, IBM Corporation, Yorktown Heights, New York, August 1967.

177. Innes, L.G. Comparison of a Linear and a Nonlinear Scale as a Gross Analogue Indication of Altitude. RCAF Report 62-RD-6 (AD 294 708), Royal Canadian Air Force, Institute of Aviation Medicine, Toronto, Ontario, November 1962.

178. Ireland, F.H. An Experimental Investigation of the Monocular and Binocular Critical Two Pulse Interval. Unpublished Ph.D. Dissertation, Fordham University, 1954.

179. Ireland, F.H., Kinslow, W., Levin, E., and Page, D. Experimental Study of the Effects of Surround Brightness and Size on Visual Performance. AMRL-TR-67-102 (AD 666 045), United States Air Force, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, September 1967.

180. Ivanoff, A. "Chromatic Aberration of the Eye." Documenta Opthalmologica, Volume 3, Pages 322-323, 1949.

181. Ivey, H.F. "Electroluminescence and Related Effects." in Advances in Electronics and Electron Physics, Supplement I, Academic Press, Inc., New York, 1963.

182. JEDEC Electron Tube Council. Optical Characteristics of Cathode Ray Tube Screens. Publication Number 16A, 1966.

183. Johnston, D.M. "Search Performance as a Function of Peripheral Acuity." Human Factors, Volume 7, Number 6, Pages 527-536, December 1965.

184. Johnston, Dorothy M. "Target Recognition on TV as a Function of Horizontal Resolution and Shades of Gray." Human Factors, Volume 10, Number 3, Pages 201-210, 1968.

185. Johnson, L.C. Flicker as Helicopter Pilot Problem: Use of Photo Stimulation and EEG as Screening Device. Proceedings of AGARD Annual Meeting, Lisbon, Portugal, 1964.

186. Jones, Mari R. "Color Coding." Human Factors, Volume 4, Number 4, Pages 355-365, 1962.

187. Koffka, K. Principles of Gestalt Psychology. Harcourt Brace and Company, New York, 1935.

188. Kamler, J. Luminescent Screens - Photometry and Colorimetry. ILIFFE Books, Ltd., London, England, 1969.

189. Kappauf, W.E. Design of Instrument Dials for Maximum Legibility: I. Development of Methodology and Some Preliminary Results. Report No. TSEAA8/PMF/jc (ATI 16325), United States Air Force, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, October 1947.

190. Kappauf, W.E. Studies Pertaining to the Design of Visual Displays for Aircraft Instruments, Computers, Maps, Charts, Tables and Graphs: A Review of the Literature. AF Technical Report No. 5765 (ATI 55956), United States Air Force, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, April 1949.

191. Kappauf, W.E. A Discussion of Scale Reading Habits. AF TR No. 6569 (ATI 122740), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, July 1951.

192. Kappauf, W.E. and Smith, W.M. Design of Instrument Dials for Maximum Legibility: II. A Preliminary Experiment on Dial Size and Graduation. Report No. MCREXD-694-1-N (ATI 33147), United States Air Force, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, July 1948.

193. Kappauf, W.E. and Smith, W.M. Design of Instrument Dials for Maximum Legibility: IV. Dial Graduation, Scale Range and Dial Size as Factors Affecting the Speed and Accuracy of Scale Reading. AF Technical Report No. 5914, Part 4 (ATI 78314), United States Air Force, Air Materiel Command, Wright-Patterson Air Force Base, Ohio, February 1950.

194. Kaufman, L., Lincoln, A.J., and Pitbaldo, C. Evaluation of Pseudo-Random Dot-Scanning Television Systems. AFCRL-67-0004 (AD 647 599), Air Force Cambridge Research Laboratories, Office of Aerospace Research, Bedford, Mass., January 1967.

195. Kelley, C.R., Ketchel, J.M., and Strudwick, P.H. Experimental Evaluation of Head-Up Display High Brightness Requirements. Technical Report No. HFR 9765-1 (AD 626 657), Kaiser Aerospace and Electronics, Palo Alto Electronics Plant, Palo Alto, California, November 1965.

196. Kelley, E.J. Gapless Electroluminescent Displays. AFFDL-TR-57 (AD 821 838), Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, August 1967.

197. Kelly, D.H. "Visual Response to Time-Dependent Stimuli. I. Amplitude Sensitivity Measurements." Journal of the Optical Society of America, Volume 51, Number 4, Pages 422-429, 1961.

198. Kelly, D.H. "Flicker Fusion and Harmonic Analysis." Journal of the Optical Society of America, Volume 51, Number 9, Pages 917-918, 1961.

199. Kelly, D.H. "Flicker Thresholds." In Nye, P. (Ed.) Information Processing in Sight Sensory Systems, C.I.T. Press, Pages 167-176, 1965.

200. Kelly, R.B. The Effect of Direction of Contrast on T.V. Legibility Under Varying Ambient Illumination. Dunlap and Associates, Inc., Stamford, Conn., June 1960.

201. Kelso, B.J. A Static Investigation of Selected Scale Characteristics for Moving-Tape Instruments. Control-Display Information Center Report No. CDIC 1241 (AD 613 612), United States Air Force, Flight Dynamics Laboratory, Control Systems Research Branch, Wright-Patterson Air Force Base, Ohio, October 1964.

202. Kelso, B.J. "Legibility Study of Selected Scale Characteristics for Moving-Tape Instruments." Human Factors, Volume 7, Number 6, Pages 545-554, December 1965.

203. Ketchel, J.M. An Investigation of the Effects of High Intensity Light Adaptation on Electronic Display Visibility. Technical Report Number HFR 12361-1 (AD 815 222), Kaiser Aerospace and Electronics Corporation, Palo Alto, California, June 1967.

204. Ketchel, J.M. "The Effects of High Intensity Light Adaptation on Electronic Display Visibility." Journal of the Society for Information Display, Volume 6, Number 3, Pages 71-76, May/June 1969.

205. Ketchel, J.M., Danaher, J.W., and Morrissey, C.J. Effects of Vibration on Navy and Marine Corps. Helicopter Flight Crews. Contract N00014-69-C-0289 (AD 698 194), Office of Naval Research, U.S. Navy Department, Washington, D.C., August 1969.

206. Ketchel, J. and Jenney, L. Electronic and Optically Generated Aircraft Displays: A Study of Standardization Requirements. JANAIR Report No. 680505 (AD 684 849), United States Navy, Office of Naval Research, Washington, D.C., May 1968.

207. King, H., Landis, C., and Zubin, J. "Visual Subliminal Perception Where Figure is Obscured by the Illumination of the Ground." Journal of Experimental Psychology, Volume 34, Pages 60-69, 1944.

208. King, R.C., Wollentin, R.W., Semple, C.A., and Goettelmann, G. Electroluminescent Display Legibility Research and Development. AFFDL-TR-70-89, Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, August 1970.

209. Kiver, M. Television Simplified. Van Nostrand Company, Inc., Princeton, New Jersey, 1967.

210. Kleitman, N. and Blier, Z.A. "Color and Form Discrimination in the Periphery of the Retina." American Journal of Physiology, Volume 85, Pages 178-190, 1928.

211. Lally, K.P. "Non-linear Optical Filters for High Contrast Displays." Society for Information Display 7th National Symposium, Boston, Massachusetts, October 1966.

212. Lansdell, H. "Effect of Form on the Legibility of Numbers." Canadian Journal of Psychology, Volume 8, Pages 77-79, 1954.

213. Leibowitz, H.W. and Lomont, J.F. The Effect of Luminance and Exposure Time Upon Perception of Motion. WADC-TR-54-78, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1954.

214. Leverenz, H. An Introduction to Luminance of Solids. Dover Publications, Inc., New York, 1968.

215. Levy, D. and Russo, A. Investigation of an Electroluminescent Symbolic Indicator. RADC-TR-65-103 (AD 618 300), Rome Air Development Center, Griffiss Air Force Base, New York, June 1965.

216. Lidoski, J. Electroluminescent Multipurpose Spacecraft Display. AFFDL-TR-69-48, Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, October 1969.

217. Lippert, S. and Lee, D.M. "Dynamic Vision: The Legibility of Moderately Spaced Alphanumeric Symbols." Human Factors, Volume 7, Number 6, Pages 555-560, December 1965.

218. Loeb, M. A Further Investigation of the Influence of Whole-Body Vibration and Noise on Tremor and Visual Acuity. MRL-Report 1955-165 (AD 55 065), U.S. Army Medical Research Laboratory, Walter Reed Hospital, 1955.

219. Loucks, R.B. Legibility of Aircraft Instrument Dials: The Relative Legibility of Various Climb Indicator Dials and Pointers. Project No. 286 Report No. 1 (AD 132 977), Army Air Force School of Aviation Medicine, Randolph Field, Texas, November 1944.

220. Luckiesh, M. Light, Vision and Seeing. D. Van Nostrand, 1944.

221. Ludvigh, E.J. "Visual Acuity While One is Viewing a Moving Object." Archives of Opthalmology, Volume 42, Pages 14-22, 1949.

222. Ludvigh, E. "The Visibility of Moving Objects." Science, Volume 108, Pages 63-64, 1948.

223. Ludvigh, E. and Miller, J.W. "Study of Visual Acuity During the Ocular Pursuit of Moving Test Objects. I. Introduction." Journal of the Optical Society of America, Volume 48, Number 11, Pages 799-802, November 1958.

224. Luxenberg, H.R. "Photometric Units." Information Display, Volume 2, Number 3, Pages 39-41, May/June 1965.

225. Luxenberg, H.R. and Bonness, Q.L. "Quantitative Measures of Display Characteristics." Information Display, Volume 2, Number 4, Pages 8-14, July/August 1965.

226. Luxenberg, H.R. and Kuehn, R.L. Display System Engineering. McGraw-Hill Book Company, New York, 1968.

227. Lythgoe, R.J. "The Measurement of Visual Acuity." Special Report Series, Medical Research Counsel, Number 173, London, 1932.

228. Mach, E. The Analysis of Sensation. (Translated 5th Edition by S. Waterlou), Open Court Publishers, Chicago, 1914.

229. Mackworth, N.H. Legibility of Raid Block Letters and Numbers. Report No. FDRC 432(S), Great Britain Air Ministry Flying Personnel Research Committee, Psychological Laboratory, Cambridge, April 1944.

230. McCormick, E.J. Human Factors Engineering. McGraw-Hill Book Company, New York, 1970.

231. McLean, M.V. "Brightness Contrast, Color Contrast, and Legibility." Human Factors, Volume 7, Number 6, Pages 521-526, December 1965.

232. Meister, D. and Sullivan, D.J. Guide to Human Engineering Design for Visual Displays. Office of Naval Research Contract Number N00014-68-C-0278 (AD 693 237), Engineering Psychology Branch, Office of Naval Research, Washington, D.C., August 1969.

233. Mengelkoch, R.F. and Houston, R.C. Investigations of Vertical Displays of Altitude Information: I. Comparison of a Moving-Tape and Standard Altimeter on a Simulated Flight Task. WADC TR 57-384 (AD 130 828), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1958.

234. Mengelkoch, R.F. and Houston, R.C. Investigations of Vertical Displays of Altitude Information: II. The Effect of Practice on Performance of a Simulated Flight Task Using a Moving-Tape Altimeter. WADC TR 57-385 (AD 130 829), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1958.

235. Mengelkoch, R.F. and Houston, R.C. Investigations of Vertical Displays of Altitude Information: III. The Effect of an Expanded Scale on Performance of a Simulated Flight Task Using a Moving-Tape Altimeter. WADC TR 57-549 (AD 142 042), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, March 1958.

236. Mercier, A. Problems of Vision in Low Level Flight. (AD 661 164), Advisory Group for Aerospace Research and Development, Paris, France, 1967.

237. Miller, G.A. "The Magical Number Seven, Plus or Minus Two: Some Limits on our Capacity for Processing Information." Psychological Review, Volume 63, Pages 81-97, 1956.

238. Miller, J.W. "Study of Visual Acuity During Ocular Pursuit of Moving Test Objects. II. Effects of Direction of Movement, Relative Movement, and Illumination." Journal of the Optical Society of America, Volume 48, Number 11, Pages 803-808, November 1958.

239. Milton, J.L., McIntosh, B.B., and Cole, E.L. Eye Fixations of Aircraft Pilots: VI. Eye Fixations During Day and Night ILAS Approaches Using an Experimental Panel Arrangement. USAF Technical Report Number 6570, United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1951.

240. Milton, J.L., McIntosh, B.B., and Cole, E.L. Eye Fixations of Aircraft Pilots: VII. Fixations During Day and Night GCA Approaches. USAF Technical Report No. 6709, United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, February 1952.

241. Mitchell, J.H. Displays I: Cathode Ray Tubes. Report Number 1954-494-03-18 (AD 039 489), Tufts College, Medford, Mass., 1954.

242. Mitchell, R.T. and Mitchell, R.R. "Visual Acuity Under Blue Illumination." IRE Transactions on Human Factors in Electronics, March 1962.

243. Mitchell, R.T. and Resnick, R. Visual Flicker on CRT Phosphors. Quarterly Progress Report Information Procurement Program, Lincoln Laboratory, Pages 49-50, June 1960.

244. Monroe, R.D., Vreuls, D., and Semple, C.A. Summary of All-Weather Landing Simulation Studies. FAA SRDS Report No. RD68-13. Systems Research and Development Service, Federal Aviation Administration, Washington, D.C., February 1968.

245. Moon, P. and Spencer, D.E. "Visual Data Applied to Lighting Design." Journal of the Optical Society of America, Volume 34, Number 10, Pages 605-617, 1944.

246. Moore, L.C. and Nida P.M. An Analysis of Lettering Styles for an Improved Raster-Type Data Display. Technical Development Report No. 378, Federal Aviation Agency, Indianapolis, Indiana, December 1958.

247. Morgan, C.T., Cook, J.S.,III, Chapanis, A. et al. Human Engineering Guide to Equipment Design. McGraw-Hill Book Company, New York, 1963.

248. Morgan, C.T. and Stellar, E. Physiological Psychology. McGraw-Hill Book Company, New York, 1950.

249. Mote, F.A. and Riopelle, A.J. "The Effects of Varying the Intensity and the Duration of Pre-Exposure Upon Subsequent Dark Adaptation in the Human Eye." Journal of Comparative Physiological Psychology, Volume 46, Pages 49-55, 1953.

250. Muller, P.F., Sidorsky, R.C., Slivinske, A.J., Alluisi, E.A., and Fitts, P.M. The Symbolic Coding of Information on Cathode Ray Tubes and Similar Displays. WADC-TR-55-375 (AD 103 239), Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1955.

251. Munn, N.L. and Geil, G.M. "A Note on Peripheral Form Discrimination." Journal of General Psychology, Volume 5, Pages 78-88, 1931.

252. Murphy, J.V., Pizzicara, D.J., Belcher, J.J., Hamson, R.L., and Bernberg, R.E. Integrated Cockpit Research Program. Appendix I. NR 213-041 (AD 658 753), Office of Naval Research, Air Programs, Washington, D.C., January 1967.

253. Myers, W.S. Accommodation Effects in Multicolor Displays. AFFDL-TR-67-161, Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, December 1967.

254. Neuman, K.M. A Comparison Between Spatial and Alphanumeric Encoding of Information on a Visual Display. Research Report 1084 (AD 670 619), U.S. Navy Electronics Laboratory, San Diego, California, December 1961.

255. Nowakowski, B.A. "The Measurement of Glare." American Journal of Hygiene, Volume 6, Number 1, Pages 1-31, January 1926.

256. Nutting, P.G. "Effects of Brightness and Contrast in Vision." Transactions of the Illumination Engineering Society, Volume 11, Pages 939-946, 1916.

257. Obert-Thorn, W.C. Visual Persistence Decay Curves as a Function of Intensity and Duration of the Stimulus. NAVTRADEVCEN IH-1 (AD 284 977), U.S. Naval Training Device Center, Port Washington, New York, June 1962.

258. Ogle, K.N. "On the Resolving Power of the Human Eye." Journal of the Optical Society of America, Volume 41, Number 8, Pages 517-520, 1951.

259. Osgood, C.E. Method and Theory in Experimental Psychology. Oxford University Press, Fair Lawn, New Jersey, 1953.

260. Panel on Psychology and Physiology. A Survey Report on Human Factors in Undersea Warfare. National Research Council, Washington, D.C., 1949.

261. Parker, J.F. Target Visibility as a Function of Light Transmission through Fixed Filter Visors. ONR Report 64-2 (AD 601 339), Office of Naval Research, Washington, D.C., April 1964.

262. Pease, G.R. A Preliminary Study of Form Perception in Peripheral Vision. Unpublished Experiment in the Psychology Laboratory of Iowa State University, 1927.

263. Peterson, C.J. Solid-State Display Techniques. AFFDL-TR-66-123, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, October 1966.

264. Peterson, C.J. and Smith, H.A. Development of High Contrast Electroluminescent Techniques for Aircraft Displays. AFFDL-TR-66-6, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, April 1966.

265. Petertyl, S.V., Fuller, P.R., and Wysocki, C.A. Development of High Contrast Electroluminescent Displays. AFFDL-TR-66-183, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, March 1967.

266. Pigg, L.D. and Kama, W.N. The Effect of Transient Weightlessness on Visual Acuity. WADC Technical Report 61-184 (AD 261 906), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1961.

267. Pizzicara, D.J. Electroluminescence an Appraisal for Avionic Display Applications. (AD 656 733), Litton Systems, Inc., Woodland Hills, California, February 1966.

268. Poole, H.H. Fundamentals of Display Systems. Spartan Books, Washington, 1966.

269. Polyak, S.L. The Retina. University of Chicago Press, Chicago, Illinois, 1941.

270. Porter, T.C. "Contributions to the Study of Flicker." Proceedings of the Royal Society (London), Volume 63, Pages 347-356, 1893.

271. Porter, T.C. "Contributions to the Study of Flicker. Paper II." Proceedings of the Royal Society (London), Volume 70, Pages 313-329, 1902.

272. Pratt, W.K. "A Bibliography on Television Bandwidth Reduction Studies." IEEE Transactions on Information Theory, Volume 13, Pages 114-115, 1967.

273. Promisel, D.M. "Visual Target Location as a Function of the Number and Kinds of Competing Signals." Journal of Applied Psychology, Volume 45, Number 6, Pages 420-427, 1961.

274. Rappaport, M. "The Role of Redundancy in the Discrimination of Visual Forms." Journal of Experimental Psychology, Volume 53, Number 1, Pages 3-10, 1957.

275. Resnick, R., Mitchell, R.T., and Gould, R.H. Visual Flicker in CRT Phosphors. Quarterly Progress Report, Pages 56-58, Information Procurement, Lincoln Laboratories, March 15, 1960.

276. Riggs, L.A. "Light as a Stimulus for Vision." In Graham, C.H. (Ed.), Vision and Visual Perception, Pages 1-38, Wiley and Sons, New York, 1965.

277. Riley, M.B. and White, W.J. "The Effects of Increased G on the Relation Between Illumination and Dial Reading." Journal of Aviation Medicine, Volume 28, Pages 109-110, 1957.

278. Rizy, E.F. Color Specifications for Additive Color Group Displays. RADL-TR-65-278 (AD 621 068), Rome Air Development Center, Research and Technology Division, Air Force Systems Command, Griffiss Air Force Base, New York, August 1965.

279. Rizy, E.F. Dichroic Filter Specification for Color Additive Displays: I. Preliminary Tolerance Determination and the C.I.E. Designations for Coding Colors. (AD 488 479), United States Air Force, Rome Air Development Center, Griffiss Air Force Base, New York, August 1966.

280. Rock, M. Visual Performance as a Function of Low Photopic Brightness Levels. Air Force Technical Report Number 6013, Wright-Patterson Air Force Base, Ohio, November 1950.

281. Roscoe, S.N. "Flight by Periscope: I. Performing an Instrument Flight Pattern; The Influence of Screen Size and Image Magnification." University of Illinois Bulletin, Aeronautics Bulletin Number 9, March 1951.

282. Roscoe, S.N. Development of Integrated Display Panels at Hughes Aircraft Company. Paper presented to the Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1956.

283. Roscoe, S.N. "Airborne Displays for Flight and Navigation." Human Factors, Volume 10, Number 4, Pages 321-332, August 1968.

284. Roscoe, S.N., Hasler, S.G., and Dougherty, D.J. "Flight by Periscope: Making Takeoffs and Landings; The Influence of Image Magnification, Practice, and Various Conditions of Flight." Human Factors, Volume 8, Number 1, Pages 13-40, February 1966.

285. Ross, R.T. "The Fusion Frequency in Different Areas of the Visual Field: IV. Fusion Frequency as a Function of the Light-Dark Ratio." Journal of Genetic Psychology, Volume 29, Pages 129-144, 1943.

286. Roth, E.M. (Ed.) Compendium of Human Responses to the Aerospace Environment, Volume I, Sections 1-6. NASA CR 1205(I), National Aeronautics and Space Administration, Washington, D.C., November 1968.

287. Rowland, G.E. and Cornog, D.Y. Selected Alphanumeric Characters for Closed-Circuit Television Displays. Technical Report #21 (AD 203 318), Civil Aeronautics Administration, Technical Development Center, Indianapolis, Indiana, July 1958.

288. Sawtelle, E.M. and Gonyou, G.W. "Dynamic CRT Spot Measurement Techniques." Information Display, Volume 6, Number 4, July/August 1969.

289. Schade, O.H. "Electro-Optical Characteristics of Television Systems. Part II." RCA Review, Volume 9, Pages 5-37, 1948.

290. Schmidt, I. "Satellite-to-Satellite Visibility." In Lectures in Aerospace Medicine, (PB 167688), Pages 100-118, Brooks Air Force Base, Texas, February 3-7, 1964.

291. Schroeder, A.C. "Theory on the Receptor Mechanism in Color Vision." Journal of the Optical Society of America, Volume 50, Number 10, Pages 945-949, 1960.

292. Schuett, E.P. Application of Passive Helicopter Rotor Isolation for Alleviation of Rotor-Induced Vibration. Kaman Aircraft Corp., Bloomfield, Connecticut, 1967.

293. Seibert, W.F. The Legibility of Televised Visuals: A Study of Signal Bandwidth and Other Factors. Unpublished Study (Instructional Media Research Unit, Purdue University, December 1964).

294. Semple, C.A. and Gainer, C.A. Phase II. Operator Display Parameters. Manned Systems Sciences, Inc., Northridge, California, April 1969.

295. Senders, J.W. Tracking with Intermittently Illuminated Displays. WADC Technical Report 55-378, Aero Medical Laboratories, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1955.

296. Senders, V.L. and Cohen, J. The Effects of Absolute and Conditional Probability Distributions : Instrument Settings on Scale Reading: Repeated Exposures of the Same Setting. WADC TR 54-253 (AD 54 628), United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1954.

297. Senders, V.L., Cohen, J., and Argintenau, M. The Effects of Absolute and Conditional Probability Distributions on Instrument Reading: II. A Comparison of a Linear and a Logarithmic Scale. WADC TR 54-253, Part 2, United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, July 1955.

298. Seris, H. and Auffret, R. Measurement of Low Frequency Vibrations in Big Helicopters and their Transmission to the Pilot. NASA TTF-471, National Aeronautics and Space Administration, Washington, D.C., May 1967.

299. Seyb, E.K. Sighting Range at Night and Twilight Brightness. SHAPE-TM-151 (AD 811 315), SHAPE Technical Centre, The Hague (Netherlands), March 1967.

300. Shanahan, D. Effects of Television Bandwidth on Target Identification. Technical Memorandum Number NMC-TM-64-2 (AD 435 746), U.S. Naval Missile Center, Point Mugu, California, April 1964.

301. Sherr, S. Display System Design. Wiley-Interscience Series, John Wiley and Sons, New York, 1970.

302. Showman, D.J. Studies of Display Symbol Legibility Part X: The Relative Legibility of Leroy and Lincoln/Mitre Alphanumeric Symbols. ESD-TR-66-115 (AD 640 170), Electronic Systems Division, Air Force Systems Command, L.G. Hanscom Field, Mass., August 1966.

303. Shurtleff, D.A. Design Problems in Visual Displays - Part I, Classical Factors in the Legibility of Numerals and Capital Letters. ESD-TR-66-62 (AD 636 414), United States Air Force, Electronic Systems Division, Hanscom Field, Bedford, Mass., June 1966.

304. Shurtleff, D.A. "Studies in Television Legibility - A Review of the Literature." Information Display, Volume 4, Pages 40-45, January/February 1967.

305. Shurtleff, D.A., Marsetta, M., and Showman, D. Studies of Display Symbol Legibility, IX: The Effects of Resolution, Size, and Viewing Angle of Legibility. ESD-TR-65-411 (AD 633 833), Electronics Systems Division, Air Force Systems Command, Hanscom Field, Mass., May 1966.

306. Shurtleff, D.A. and Owen, D. Studies of Display Symbol Legibility, VI: A Comparison of the Legibility of Televised Leroy and Courtney Symbols. ESD-TR-65-136 (AD 633 855), Electronic Systems Division, Air Force Systems Command, Hanscom Field, Mass., May 1966.

307. Shurtleff, D.A. and Owen, D. Studies of Display Symbol Legibility, VII: The Legibility of Leroy Symbols on a 945-Line and 525-Line Television System. ESD-TR-65-137 (AD 633 649), Electronic Systems Division, Air Force Systems Command, Hanscom Field, Mass., May 1966.

308. Simon, C. and Roscoe, S. Altimetry Studies: II. A Comparison of Integrated Versus Separated, Linear Versus Circular, and Spatial Versus Numerical Displays. Technical Memorandum No. 435, Weapon Systems Development Laboratories, Hughes Aircraft Company, Culver City, California, May 1956.

309. Sleight, R.B. "The Effect of Instrument Dial Shape on Legibility." Journal of Applied Psychology, Volume 32, Pages 170-188, 1948.

310. Sleight, R.B. "The Relative Discriminability of Several Geometric Forms." Journal of Experimental Psychology, Volume 43, Pages 324-328, 1952.

311. Sloan, L.L. "Rate of Dark Adaptation and Retinal Threshold Gradient of the Dark Adapted Eye: Physiologic and Clinical Studies." American Journal of Opthalmology, Volume 30, Pages 705-720, 1947.

312. Slocum, G.K., Hoffman, W.C., and Heard, J.L. "Airborne Sensor Display Requirements and Approaches." Information Display, Volume 4, Number 6, November/December 1967.

313. Smedal, H.A., Greer, B.Y., and Wingrove, R.C. "Abilities of Pilots to Perform a Control Task in Various Sustained Acceleration Fields." Aerospace Medicine, Volume 31, Pages 901-906, 1960.

314. Smith, A. and Boyes, G. "Visibility on Radar Screens: The Effect of CRT Bias and Ambient Illumination." Journal of Applied Psychology, Volume 41, Number 1, Pages 15-18, 1957.

315. Smith, S.L. Display Color Coding for a Visual Search Task. Technical Report MTS-7 (AD 283 971), Mitre Corporation, Bedford, Mass., June 1962.

316. Smith, S.L. and Farquhar, Barbara. "Color Coding in Formatted Displays." Journal of Applied Psychology, Volume 49, Number 6, Pages 393-398, 1965.

317. Smith, S.L. and Thomas, D.W. "Color Versus Shape Coding in Information Displays." Journal of Applied Psychology, Volume 48, Number 3, Pages 137-146, June 1964.

318. Snadowsky, A.M., Rizy, E.F., and Elias, M.F. Misregistration in Color Additive Displays. RADC-TDR-64-488 (AD 610 528), Rome Air Development Center, Research and Technology Division, Air Force Systems Command, Griffiss Air Force Base, New York, 1964.

319. Soar, R.S. "Height-Width Proportions and Stroke Width in Numeral Visibility." The Journal of Applied Psychology, Volume 39, Number 1, Pages 43-46, 1955.

320. Southall, J.P.C. Introduction to Physiological Optics. Dover Publishing Company, New York, 1961.

321. Steedman, W.C. and Baker, C.A. Target Size and Visual Recognition. WADD Technical Report 60-93 (AD 235 129), Aerospace Medical Laboratory, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, February 1960.

322. Steinhardt, J. "Intensity Discrimination in the Human Eye: I. The Relation of ΔI/I to Intensity." Journal of General Psychology, Volume 20, Pages 185-209, 1936.

323. Stephenson, S.D. and Schiffler, R.J. The Relative Ligibility of Five Different Segmented Electroluminescent Fonts. RADC-TR-68-372, Rome Air Development Center, Griffiss Air Force Base, New York, September 1968.

324. Stevens, H.C. "The Peculiarities of Peripheral Vision." Psychological Review, Volume SV, Number 2, Pages 69-93, 1908.

325. Stiles, W.S. "The Effects of Glare on the Brightness Difference Threshold." Proceedings of the Royal Society (London), Volume 104B, Pages 322-351, 1929.

326. Stiles, W.S. and Crawford, B.H. "The Luminous Efficiency of Rays Entering the Eye Pupil at Different Points." Proceedings of the Royal Society (London), Volume 112-B, Pages 428-450, March 1933.

327. Taub, H.A. The Effects of Vibration on Dial Reading Performance. AMRL-TDR-64-70 (AD 603 963), Biophysics Laboratory, Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, July 1964.

328. Taylor, J.H. Contrast Thresholds as a Function of Retinal Position and Target Size for the Light-Adapted Eye. SJO Reference-61-10 (AD 296 243), Scripps Institute of Oceanography, University of California, La Jolla, California, March 1961.

329. Thomas, D.R. "Exposure Time as a Variable in Dial Reading Experiments." Journal of Applied Psychology, Volume 41, Number 3, Pages 150-152, May 1957.

330. Topmiller, D.A. "The Effect of Stroke Width on Linear Interpolation." Journal of Applied Psychology, Volume 39, Number 4, Pages 273-276, August 1955.

331. Tufts College, Experimental Psychology Institute. Handbook of Human Engineering Data, NAVEXOS P-643, November 1952.

332. Turnage, R.E. "The Perception of Flicker in Cathode Ray Tubes." Information Display, Volume 3, Pages 38-52, May/June 1966.

333. Turnage, R.E. "Compensating for Two Types of CRT Distortion." Electron Design, Volume 9, Pages 62-64, May 11, 1964.

334. Ulett, G. "Flicker Sickness." Archives of Opthalmology, Volume 50, Number 6, Pages 685-687, 1953.

335. Vartebedian, A.G. "Effects of Parameters of Symbol Formation on Legibility." Journal of the Society for Information Display, volume 7, Number 5, Pages 23-26, 1970.

336. Vernon, M.D. Scale and Dial Reading. Report Number APU.49 (ATI 84856), Flying Personnel Research Committee, Medical Research Council Unit of Applied Psychology, Psychological Laboratory, Cambridge, England, July 1946.

337. Vos, J.J. Some Considerations on Eye Hazards with Lasers. TDCK-46027 (N66 39840), National Defense Research Council, TNO, Medical Biological Laboratory, Rijswijk, Netherlands, 1966.

338. Vreuls, D. and Schmidt, J.F. "Model for Effect of a Second Visual Stimulus Upon Reaction Time to the First." Perceptual and Motor Skills, Volume 23, Pages 323-328, 1966.

339. Wallace, F.L. "Head-Up Displays - Some Unanswered Questions." In Proceedings of the 15th Airline Pilots Association Air Safety Forum, AIAA Publication No. A69-20452, American Institute of Aeronautics and Astronautics, Inc., 750 Third Avenue, New York, New York, July 1968.

340. Walsh, J.W.T. Photometry. Dover Publications, Inc., New York, 1965.

341. Warrick, M.J. and Lund, D.W. Effect of Moderate Positive Acceleration (G) on Ability to Read Aircraft-Type Instrument Dials. TSEAA-694-10 (ATI 110567), U.S. Air Force Air Material Command, Wright-Patterson Air Force Base, Ohio, November 1946.

342. Weasner, H.M. "Target Detectability as a Function of the Area of Search with Various Degrees of Noise Present." In Brown, R.H. (Ed.), Illumination and Visibility of Radar and Sonar Displays, Publication 595, National Academy of Sciences, National Research Council, Washington, D.C., 1958.

343. Webb Associates. NASA Life Sciences Data Book. (First Edition), Director of Aerospace Medicine, Office of Manned Space Flight Headquarters, National Aeronautics and Space Administration, Washington, D.C., June 1962.

344. Webb, P. (Ed.) Bioastronautics Data Book. NASA SP-3006, National Aeronautics and Space Administration, Washington, D.C., 1964.

345. Weiss, H. "Optimum Spot Size of a Scanned CRT Display." Information Display, Volume 6, Number 6, Pages 51-52, November/December 1969.

346. White, W.J. "Visual Performance Under Gravitational Stress." In O. H. Gauer and G.D. Zuidema (Eds.), Gravitational Stress in Aerospace Medicine, Boston: Little, Brown, and Company, Pages 70-89, 1961.

347. White, W.J. The Effects of Transient Weightlessness: On Brightness Discrimination. AMRL-TDR-64-12 (AD 435 544), Behavioral Sciences Laboratory, Aerospace Medical Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, March 1964.

348. White, W.J. Acceleration and Vision. WADC-TR-58-333 (AD 208 147), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1958.

349. White, W.J. and Jorve, W.R. The Effects of Gravitational Stress Upon Visual Acuity. WADC Technical Report 56-247 (AD 110 444), Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, November 1956.

350. White, W.J. and Monty, R.A. "Vision and Unusual Gravitational Forces." Human Factors, Volume 5, Number 3, Pages 239-264, 1963.

351. White, W.J. and Riley, M.B. The Effects of Positive Acceleration on the Relation Between Illumination and Instrument Reading. WADC-TR-58-332 (AD 206 663), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, November 1958.

352. Whitham, G.E. "The Determination of Display Screen Size and Resolution Based on Perceptual and Information Limitations." Information Display, Volume 2, Number 4, Pages 15-19, July/August 1965.

353. Whitmer, C.A. "Peripheral Form Discrimination Under Dark-Adaptation." Journal of General Psychology, Volume 9, Pages 405-419, 1933.

354. Wilcox, W.W. "The Basis of the Dependence of Visual Acuity on Illumination." Proceedings of the National Academy of Science, Volume 18, Pages 47-57, 1932.

355. Wilkinson, F.R. "The Initial Perception of Pulses of Light." Journal of Psychology, Volume 43, Pages 265-268, 1957.

356. Williams, C.R. Preliminary Analysis of Information Required by Pilots for Instrument Flight. ONR Report Number 70-16-1, Office of Naval Research, Special Devices Center, April 1947.

357. Williams, J.R. and Falzon, R.P. "Relationship of Some Display System Variables to Symbol Recognition and Search Time." Journal of Engineering Psychology, Volume 2, Number 3, Pages 97-111, July 1963.

358. Williams, J.R. and Falzon, R.P. "Comparison of Search Time and Accuracy Among Selected Outlined Geometric Forms." Journal of Engineering Psychology, Volume 2, Number 3, Pages 117-118, July 1963.

359. Williams, P. Technical Progress Report on Universal Contact Analog Display (UCAD) Research: Phase I - Systems Analysis. Report No. 1161 R 0011 (AD 616 650), Joint Army-Navy Aircraft Instrumentation Research Committee, Office of Naval Research, Washington, D.C., April 1965.

360. Woodson, W.E. and Conover, D.W. Human Engineering Guide for Equipment Designers. University of California Press, Berkeley, California, 1964.

361. Woodworth, R.S. and Schlosberg, H. Experimental Psychology (Revised Edition). Holt Company, New York, 1954.

362. Wright, W.D. "The Sensitivity of the Eye to Small Color Differences." Proceedings of the Physical Society of London, Volume 53, Pages 93-112, 1941.

363. Wulfeck, J.W., Weisz, A., and Raben, M. Vision in Military Aviation. WADC-TR-58-399 (AD 207 780), Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, November 1958.

364. Wurtz, J.E. "High Resolution Cathode Ray Tubes for the System Designer." Information Display, Volume 4, Number 3, Pages 39-45, May/June 1967.

365. Ziegler, P.N., Reilly, R.E., and Chernikoff, R. The Use of Displacement, Flash, and Depth-of-Flash Coded Displays for Providing Control Information. NRL Report 6412 (AD 639 644), Engineering Psychology Branch, U.S. Navy Research Laboratory, Washington, D.C., July 1966.

366. Zworykin, V.K. and Morton, G.A. Television. Second Edition. John Wiley and Sons, New York, 1954.

367. Simon, C.W. "Rapid Acquisition of Radar Targets from Moving and Static Displays." Human Factors, Volume 7, Number 3, Pages 185-205, June 1965.

368. Feddersen, W.E. Experimental Evaluation of an Eight-Inch CRT Contact Analog Presentation. Bell Helicopter Company Technical Report Number D228-421-011 (AD 294 781), May 1962.

369. Halsey, R.M. and Chapanis, A. "On the Number of Absolutely Identifiable Hues." Journal of the Optical Society of America, Volume 41, Number 12, Pages 1057-1058, 1951.

370. Smith, S.L. Display Color Coding and the Legibility of Overprinted Symbology. ESD-TDR-63-246 (AD 417 278), Decision Sciences Laboratory, Electronic Systems Division, Air Force Systems Command, L.G. Hanscom Field, Bedford, Mass., August 1963.

371. Eriksen, C.W. Multidimensional Stimulus Differences and Accuracy of Discrimination. WADC-TR-54-165 (AD 50 076), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, June 1954.

372. Vreuls, D., Barnebey, S.F., Brown, J.E., and Nichols, B.E. Evaluation of Flight Director Elements - Rising Runway, Expanded Localizer, and Rollout Steering - During Simulated Category III-C Manual and Split-Axis Landings. SRDS Report No. 68-10, Federal Aviation Administration, Systems Research and Development Service, Washington, D.C., February 1968.

373. Aberdeen Research and Development Center. Human Factors Engineering Design Standard for Communication Systems and Related Equipment. HEL Standard S-7-68 (AD 631 663), Aberdeen Proving Ground, Maryland, December 1968.

374. Brown, F.R. A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels. IV: Legibility of Uniform Stroke Capital Letters as Determined by Size and Height to Width Ratio and as Compared to Garamond Bold. Report TED Number NAMEL-609 (AD 10 211), Naval Air Material Center, Philadelphia, Penn., March 1953.

375. Kosmider, G. Studies of Display Legibility, V: The Effects of Television Transmission on the Legibility of Common Five-Letter Words. ESD-TR-65-135, The Mitre Corporation, Bedford, Mass., May 1966.

376. Seibert, W.F., Kaster, D.F., and Potter, J.R. "A Study of Factors Influencing the Legibility of Televised Characters." Journal of the Society of Motion Picture and Television Engineers, Volume 68, Pages 467-472, 1959.

377. Stenson, H.H. Human Factors in the Design of Electroluminescent Displays for Aerospace Equipment. AMRL-TR-66-130 (AD 646 459), Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1966.

378. McLean, M.V. and Miller, G.F. Electroluminescent Test Number One. Interim Report CSU 402059, North American Space and Information Systems, March 1965.

379. Buschow, Karen L. Readability of Digital Readout Displays. Human Engineering Special Studies Memorandum Number 10, Lockheed-Georgia Company, Georgia, November 1966.

380. Reinwald, F.L. Legibility of Symbols of the AND 10400, Mackworth, and Berger Type-Faces at Vertical and Horizontal Angles of Presentation. Science Report Number 1, Prepared Under Contract AF 30(602)-212 for Rome Air Development Center, Rome, New York, by the Department of Psychology, Colgate University, 1953.

381. Cohen, J. and Webb, I.B. An Experiment on the Coding of Numerals for Tape Presentation. WADC-TR 54-86 (AD 43 529), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, December 1953.

382. Alluisi, E.A. and Martin, H.B. "An Information Analysis of Verbal and Motor Responses to Symbolic and Conventional Arabic Numerals." Journal of Applied Psychology, Volume 42, Pages 79-84, 1958.

383. Fried, C. A Human Factors Evaluation of Seven Digital Readout Indicators. Technical Memorandum 5-60 (AD 243 030), U.S. Army Ordnance Human Engineering Laboratories, Aberdeen Proving Ground, Maryland, July 1960.

384. Kershner, A.M. and Avery, D.L. A Study in Information Processing Electroluminescent vs Teletype Readability of Weather Messages. ESD-TR-66-149 (AD 630 636), Electronic Systems Division, L.G. Hanscom Field, Bedford, Mass., December 1965.

385. Hecht, S., Haig, C., and Wald, G. "Dark Adaptation of Retinal Fields of Different Size and Location." Journal of General Physiology, Volume 19, Pages 321-339, 1935.

386. Bartley, S.H. "The Neural Determination of Critical Fusion Frequency." Journal of Experimental Psychology, Volume 21, Pages 237-239, 1937.

387. Levine, D. Information Cells on Intensity Modulated Cathode-Ray Tubes. WADC Technical Report 53-90, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, May 1952.

388. Paige, L.D. and Kama, W.N. "Visual Acuity in Relation to Body Orientation and G-Vector." Journal of Engineering Psychology, Volume 4, Number 2, Pages 45-56, 1965.

389. Paige, L.D. and Kama, W.N. "Effects of Transient Weightlessness on Visual Acuity." Journal of Engineering Psychology, Volume 4, Number 2, Pages 33-44, 1965.

390. Marsetta, M. and Shurtleff, D. Studies in Display Symbol Legibility, Part XIV: The Legibility of Military Map Symbols on Television. MTR 264, The Mitre Corporation, Bedford, Massachusetts, September 1966.

391. Postman, L. and Egan, J. Experimental Psychology: An Introduction. Harper Brothers, Publishers, New York, 1949.

392. Helson, H. and Steger, J.A. "On the Inhibitory Effects of a Second Stimulus Following the Primary Stimulus to React." Journal of Experimental Psychology, Volume 64, Number 3, Pages 201-205, September 1962.

393. Pizzicara, J.D. Computer and Displays/Controls State-of-the-Art. Joint Army/Navy Aircraft Instrumentation Program Publication 4902 (AD 631 663), Litton Systems, Inc., Guidance and Control System Division, Woodland Hills, California, February 1966.

394. Niven, J.I. et al. The Elevator Illusion. Flying Personnel Research Committee Report 1213, Air Ministry, London, 1963.

395. Lange, K.O. and Coermann, R.R. "Visual Acuity Under Vibration." Human Factors, Volume 4, Number 5, Pages 291-300, October 1962.

396. Beste, F.J. Jr. High Resolution TV as it Relates to Image Orthicon Cameras Used in Medical and Industrial X-Ray Fluroscopy. Telecommunications, Inc., Cockeysville, Maryland, May 1963.

397. Chinn, H.A. Television Broadcasting. McGraw-Hill Company, Inc., New York, 1953.